Field Assessment of the Occurrence of Algal Biofilm on Submerged Tailings

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Field Assessment of the Occurrence of Algal Biofilm on Submerged Tailings

Report prepared by:
Y.T.J. Kwong, P. Huntsman-Mapila and J. Chaulk
CANMET Mining and Mineral Sciences Laboratories
555 Booth Street
Ottawa, ON K1A 0G1

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EXECUTIVE SUMMARY

A study was conducted on biofilm formation on submerged mine tailings with the following primary objectives:

1. determine if photosynthetic biofilms are generally present on submerged mine tailings;
2. identify the physico-chemical conditions favorable for biofilm formation; and,
3. clarify the effects of biofilm on metal mobilization, where appropriate.

Five mine sites located across Northern Ontario and Quebec with submerged tailings of different compositions were selected for examination. These include:

1. Tailings impoundment at the closed Louvicourt copper mine in Val d'Or;
2. Small natural pond partially filled with mine tailings at the Nova Scotia silver mine in the historic Cobalt mining camp;
3. Oxidation pond of the Strathcona nickel mine, Onaping Operation northwest of Sudbury;
4. Tailings pond of the historic Hardy nickel mine in Onaping; and,
5. Tailings management area 1 (TMA1) of the former Denison uranium mine in Elliot Lake.

The occurrence of a continuous microbial mat overlying submerged tailings was not observed in any of the five sites examined. At the tailings pond of Louvicourt Mine and the oxidation pond of Strathcona Mine, only loose patches of iron oxyhydroxide of less than 5 mm thickness and colonized with a microbial population were found scattered over the tailings. This contrasted with previous observations made at one of the field test cells studied in 2007 at the Louvicourt Mine, where a biofilm layer up to 5 cm thickness colonized the entire tailings/water interface (Vigneault et al., 2007, MEND Report 2.12.2).

A comparison of the environmental settings between the former Louvicourt field cells and the five sites visited for this study suggests that the requirements for the formation of continuous algal biofilm may include the following:

1. A shallow, oxygenated water cover with sufficient light and heat penetration
2. A relatively quiescent environment, i.e., no active tailings movement
3. A suitable substrate for the microbial population to propagate

Based on the findings of the field and laboratory assessments, the following conclusions can be drawn:

1. Given that microbial mats were not found in any of the study sites, its formation over submerged tailings does not appear to be a common phenomenon.

2. Until further studies reveal the presence of continuous microbial mats over submerged tailings at Canadian mine sites, and the physico-chemical or ecological constraints on the establishment of biofilm are well-defined it is premature to develop new technologies to encourage biofilm formation over submerged tailings despite its beneficial effects.

3. Further research on the influence of microbes on metal mobility under both acidic and neutral conditions is recommended for developing sustainable strategies in managing submerged mine wastes.

RÉSUMÉ

Une étude sur la formation de biofilms sur les résidus miniers submergés a été réalisée en tenant compte de trois objectifs principaux :

1. déterminer si, en général, on trouve des biofilms photosynthétiques sur les résidus miniers submergés;
2. déterminer les conditions physico-chimiques propices à la formation de biofilms;
3. établir clairement les effets des biofilms sur la mobilisation des métaux, le cas échéant.

Aux fins de l'étude, on a retenu cinq sites miniers, localisés dans le nord de l'Ontario et du Québec, où l'on trouve des résidus submergés de compositions diverses. Il s'agit :

1. le parc à résidus de la mine de cuivre Louvicourt (maintenant fermée) située à Val-d'Or;
2. d'un petit étang naturel partiellement rempli de résidus miniers à la mine d'argent Nova Scotia située au camp minier historique de Cobalt;
3. d'un bassin d'oxydation à la mine de nickel de Strathcona, exploitation Onaping au nord-ouest de Sudbury;
4. du parc à résidus sur le site historique de la mine de nickel Hardy, à Onaping;
5. de la zone de gestion des résidus 1 (TMA1) de l'ancienne mine d'uranium Denison, à Elliot Lake.

La présence d'un tapis microbien recouvrant toute la surface des résidus submergés n'a été constatée à aucun des cinq sites à l'étude. Au parc à résidus de la mine Louvicourt et au bassin d'oxydation de la mine Strathcona, on a seulement trouvé des amas non consolidés d'oxyde-hydroxyde de fer mesurant moins de 5 mm d'épaisseur et colonisés par une population microbienne, dispersés sur les résidus. Cette situation contraste avec les observations précédentes faites en 2007 à l'une des cellules d'essai

à la mine Louvicourt, où une couche de biofilm d'une épaisseur allant jusqu'à 5 cm colonisait toute l'interface résidus-eau (Vigneault *et al.*, 2007, rapport NEDEM 2.12.2).

Une comparaison des cadres environnementaux des cellules d'essai à l'ancienne mine Louvicourt et des cinq sites visités dans le cadre de la présente étude permet de croire que la formation d'un biofilm algal pourrait dépendre, entre autres choses, des conditions suivantes :

1. une couverture d'eau peu profonde et oxygénée, avec une pénétration suffisante de la lumière et de la chaleur;
2. un environnement relativement calme, c.-à-d. sans mouvement des résidus;
3. un substrat adéquat pour que la population microbienne puisse proliférer.

D'après les résultats des évaluations sur le terrain et en laboratoire, il est possible de tirer les conclusions suivantes :

1. Puisque l'on n'a pas trouvé de tapis microbiens aux sites à l'étude, il semblerait que leur formation sur des résidus submergés ne soit pas un phénomène courant.
2. Tant que d'autres études n'auront pas révélé la présence de tapis microbiens permanents sur les résidus submergés dans les sites miniers canadiens et que les contraintes physico-chimiques ou écologiques pour la formation de biofilms n'auront pas été bien définies, il serait prématuré de mettre au point de nouvelles technologies pour favoriser la formation de biofilms sur les résidus submergés, et ce malgré leurs effets utiles.

3. Il est recommandé de réaliser d'autres recherches sur l'influence des populations microbiennes sur la mobilité des métaux dans des conditions acides ou neutres en vue d'élaborer des stratégies durables pour la gestion des rejets miniers submergés.

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INTRODUCTION

A recent MEND study at the Louvicourt Mine located near Val d'Or, Quebec, revealed that the establishment of a biofilm layer over submerged tailings could limit sulphide oxidation and metal mobilization in the long term (Vigneault et al., 2007). The study was conducted in the field cells (21 m x 21 m x 3 m) with a uniform, shallow water cover of 30 cm. A continuous algal mat up to 5 cm thick was found covering the entire tailings surface. Oxygen was generated by photosynthesis on the surface of the algal mat but reducing conditions were found at the bottom. The former enhanced precipitation of ferrihydrite, which scavenged dissolved metals, and the latter hampered further oxidation of the submerged sulphidic tailings. The net effect was continual reduction in efflux of metals from the tailings porewater to the overlying water column.

While the existence of the algal mat appeared to provide a benefit, it is not known to what extent biofilms occur in the Louvicourt main tailings impoundment or at other mine sites across Canada. In addition, the environmental conditions required to sustain biofilm formation are unknown. Thus it is desirable to conduct field analysis at selected mine sites with submerged tailings to assess the presence of algal biofilm and the associated water quality and limnological characteristics so that the effect of biofilm on metal mobilization can be determined. This is a necessary preliminary step to establish if further research is warranted to develop new technologies utilizing biofilm formation to enhance the performance of subaqueous tailings disposal.

To address the knowledge gaps on biofilm formation on submerged mine tailings, a study was initiated in September 2009. The primary objectives of the study are as follows:

1. determine if photosynthetic biofilms are generally present on submerged mine tailings;
2. identify the physico-chemical conditions associated with their formation; and,
3. clarify the effects of biofilm on metal mobilization, where appropriate.

To meet budgetary constraints for the project and to include a diversity of mineral deposits, five mine sites located across northern Ontario and Quebec with submerged tailings of different compositions were selected for examination (Figure 1). These sites were:

1. the tailings impoundment at the now closed Louvicourt copper mine in Val d'Or;
2. a small natural pond partially filled with mine tailings at the Nova Scotia silver mine in the historic Cobalt mining camp;
3. the oxidation pond of the Strathcona nickel mine, Onaping Operation northwest of Sudbury;
4. the tailings pond of the historic Hardy nickel mine in Onaping; and,
5. the tailings management area 1 (TMA1) of the former Denison uranium mine in Elliot Lake.

The field work was conducted in September, following a cool and very wet summer.

This is a preliminary study, and therefore the field investigations and the subsequent laboratory analyses are not comprehensive. The primary goal was to gather sufficient information to determine if further research is warranted. It should be noted that field work was conducted at all five sites within a single week, and as all the sites are located close together, climatic variation was not taken into consideration in this study.

This report is divided into four main parts. Firstly, the scope and methods of the field investigation and subsequent complementary laboratory analyses are described. Secondly, a summary of the field data and test results is presented. These data are then integrated with pertinent findings from available literature to elucidate the causes and effects of biofilm formation on submerged mine tailings. This is followed by a summary of lessons learned from the field program. Lastly, conclusions are drawn from the field and laboratory observations along with several recommendations for further work.

Figure 1 Location of the five mine sites visited for the study. Individual satellite images in Appendix A show the exact location of tailings impoundment and sampling stations at each site.

FIELDWORK AND METHODS

To minimize disturbance to the submerged tailings, a non-motorized rubber boat (Zodiac) was employed for sampling at all the tailings sites. A visual field survey was used to probe for biofilm formation and water and sediment samples were collected at locations suspected to be most promising in hosting a microbial population. Due to the lack of a boat engine, only small areas (typically 100 m by 100 m) of the more sheltered parts of an impoundment (with water depths of less than 2 m) were investigated and sampled at each site.

Typically two to three sampling locations were selected for sampling and water/sediment profiling at each site. The detailed co-ordinates of the sampling locations were recorded using a GPS (Garmin 76CSx), which facilitated the acquisition

of pertinent Google maps to show the general setting and the areas of sampling relative to the entire tailings management facilities (Appendix A). The GPS was also interfaced with a YSI 650 MDS data logger connected to a YSI 6600 V2-4 Sonde unit for measuring depth profiles of temperature, pH, conductivity, dissolved oxygen and turbidity. At each location, two 500 mL stock bottles of pond water were collected from just below the surface of the water cover. In addition, field blanks were taken for quality control purposes. The sampling bottles were rinsed three times prior to filling to the rim.

The water samples (except for a small portion saved for total chlorophyll-A analysis) were filtered (0.45 µm cellulose nitrate filter for metals and a glass fiber filter (GFF) for dissolved carbon and nutrients) either on site during the day, or later the same evening. Parameters analyzed on the day of sampling included nitrate and phosphate and total chlorophyll-A for the corresponding unfiltered samples. Aliquots of the filtered samples were saved for later analysis in the CANMET-MMSL Analytical Services Laboratory. Aliguots for dissolved metals were preserved with ultrapure nitric acid to pH <2, while those for dissolved carbon (total, organic and inorganic) analysis did not require any field preservation. All the collected samples were temporarily stored in coolers under ice for transport prior to their analysis in the field or in the laboratory.

The nitrate content of the filtered samples was measured on site or in the evening using a Hach instrument DR2800, according to Method 344N, and calibrated with a 20 mg/L NO_3^- standard solution. Phosphate was determined using the Hach DR2800, according to Method 535P, and calibrated with a 1 mg/L PO_4^{3-} standard solution. *In vivo* determinations of chlorophyll-A were made using a fluorometric method with a Turner Trilogy instrument. It should be noted that *in vivo* readings are qualitative in nature and provide only an indication of the relative chlorophyll concentrations for a range of values.

One or two sediment cores were taken at each site with transparent plexiglass tubes of 1 m in length and 5.1 cm in inner diameter. When the texture of the submerged tailings was too granular or fluid to take a core sample, a bulk sample was collected with an

Eckman sampler from which a sediment profile was extracted with a shorter tube (<30 cm long) where feasible. For both sampling methodologies, the sediment profile retained an overlying water layer of at least 10 cm thick. The sediment profiles were capped, kept cool and transported back to the laboratory intact for further processing. Attempts to determine microprofiles of pH and dissolved oxygen across the sediment/water interface were to be made *in situ* where a continuous biofilm layer was found.

LABORATORY ANALYSES AND METHODS

Water samples

Total carbon (TC) and total organic carbon (TOC) of the water samples were measured using a TC analyzer (Model TOC-VCSH, Shimadzu Scientific Instruments Inc.). The TOC was measured by the direct non-purgeable organic carbon (NPOC) method. Two external quality controls (certified reference waters ION-95, natural lake water, and MIRAMICHI-02, soft river water, Environment Canada) and internal quality controls (potassium hydrogen phthalate dissolved in double deionized water) were analyzed with every batch of samples. The TC recovery rates were 101% for ION-95 and 100% for MIRAMICHI-02. The NPOC recovery rates were 94% for ION-95 and 91% for MIRAMICHI-02.

The NPOC method is preferred because dissolved CO_2 present in air and adsorbed during sample storage and preparation is eliminated shortly prior to TOC analysis. For the NPOC method, the samples were acidified with 2N HCl and purged for 2 minutes before the NPOC analysis. Regular sensitivity catalyst was used and the samples were injected in 50 µL for 3 times.

The dissolved metals in the water samples were scanned by inductively coupled plasma mass spectrometry (ICPMS). The ICPMS scan is semi-quantitative in nature but

sufficiently accurate for comparing metal levels in various samples from the same sites and among different sites.

Sediment cores

The pH and dissolved oxygen profiles across the water/sediment interface were measured using microelectrodes to a depth of 1 – 1.5 cm as described in MEND report 2.12.2 (Vigneault et al., 2007). The overlying water was then removed and the core subdivided into sections according to visible difference in the sediment colour and/or texture. The porewater from each core section was extracted by centrifugation at 15,000 rpm for 10 minutes, and the contained metals determined by ICPMS scan. The solids were freeze-dried and a subsample was examined under a variable-pressure scanning electron microscope (VP-SEM, Hitachi S-3200N) equipped with an EDX analyzer, following the same procedure as previously described in Vigneault et al. (2007). Another subsample of the freeze-dried sediment was pulverized and its mineralogy determined by X-ray diffraction using a Rigaku D/MAX 2500 rotating anode powder diffractometer with monochromatic CuKα radiation.

RESULTS AND INTERPRETATION

Field Observations and Measurements

The occurrence of a continuous microbial mat overlying submerged tailings was not observed at any of the five sites. However, other observations were noted at the various sites, and these are described below.

At the tailings pond of Louvicourt Mine, only loose patches of iron oxyhydroxide of less than 5 mm thickness and colonized with a microbial population were found scattered over the tailings area surveyed (Figure 2). This contrasts with previous observations made at one of the field test cells where a biofilm layer up to 5 cm in thickness

colonized the entire tailings/water interface (Vigneault et al., 2007, MEND Report 2.12.2).

At the historic Nova Scotia Mine, a natural pond partially filled with submerged tailings and located down-gradient of the on-land tailings impoundment was surveyed. The pond did not contain evidence of an algal biofilm, but was populated with scattered aquatic weeds, which occupied up to 5% of the available surface area.

In the tailings pond of the historic Hardy Mine, only sparse high-order plants were encountered. In the Oxidation Pond of the Strathcona Mine Onaping Operation, scattered biofilm patches were observed. These were associated with precipitating iron and manganese oxyhydroxides, but occurred at a lower quantity than that observed at the main tailings impoundment of the Louvicourt Mine.

In the TMA1 of the former Denison Mine, black, slimy deposits of unknown thickness were unevenly distributed in a small area at the north end of the impoundment, near the entry point of the stream connecting TMA1 and TMA2. Judging from the smell of hydrogen sulphide, the slimy deposits were probably dominated by sulphate-reducing bacteria. Limited by time and sampling gear, the extent of occurrence of the slimy deposit, in other parts of the impoundment was not investigated.

Figure 2 Loose patches of biofilm found on submerged tailings at the Louvicourt tailings impoundment.

As a continuous biofilm layer was not found in any of the five sites visited, *in-situ* microprofiling of pH and dissolved oxygen across the tailings/overlying water interface would not give significantly different results than those measured from the collected sediment cores. Accordingly, i*n-situ* microprofiling was not conducted. However, the physical and chemical characteristics of the water cover at each site, including water depth, turbidity, pH, specific conductance, dissolved oxygen, nutrient and chlorophyll-A contents were measured. The collected data are summarized in Table 1.

Whereas the depth of the water covers at the Louvicourt and Hardy Mines appeared to be uniform, those at the other three sites was not and could be deeper at some other areas than those monitored at the sampling locations. Deeper water covers (e.g. Louvicourt and Moose Lake at Strathcona) generally had a lower temperature than the shallower covers (e.g. Nova Scotia and Hardy Mines). With near zero turbidity measurements, the water covers at all sites were relatively free of suspended particles,

with the exception of Moose Lake, which is an active tailings pond. The overlying water in Moose Lake was slightly acidic (pH 5.7-5.8) and those of Louvicourt and Hardy Mines were near-neutral. The water covers of the Nova Scotia pond and Denison TMA1 were slightly basic. With specific conductance measurements in excess of 2 mS/cm, the water cover of Moose Lake also contained high total dissolved solids. In contrast, the water cover at the Hardy Mine had extremely low specific conductance. At the other three sites, the water columns are characterized by dissolved solids contents that are moderately low (Nova Scotia pond) to slightly elevated (Louvicourt and Denison TMA1). At all the five sites, the water column was well oxygenated, with dissolved oxygen measurements greater than 75% saturation.

Table 1 – Physical and chemical characteristics of the water cover at the five sites visited

	Louvicourt	*Nova Scotia*	*Hardy*	*Moose Lake*	*Denison TMA1*
Maximum sampling depth (m)	1.06	0.53	0.54	1.06	0.85
Temperature (deg.C)	16.1 - 16.2	18.3 - 18.4	19.2 - 19.8	16.6 - 16.9	17.3 - 17.6
Turbidity (NTU)	-0.3 - -0.3	-0.5 - -0.2	-0.6 - -0.5	11- 30	-0.4 - -0.2
pH (pH unit)	6.1 - 6.8	7.5 - 7.8	7.1 - 7.1	5.7 - 5.8	7.9 - 8.6
Specific conductance (µS/cm)	560	220	45	2240 - 2250	460
Dissolved oxygen (mg/L)	9.3 - 9.5	9.1 - 9.3	8.7 - 8.8	6.8 - 7.0	8.1 - 8.9
Chlorophyll-A (µg/L)	1.5 - 2.2	0.8 - 1.2	0.8 - 0.9	0.0 - 0.1	0.4 - 0.5
Phosphate (mg/L)	0.00 - 0.01	0.18 - 0.26	0 - 0.02	0.07 - 0.09	0.00
Nitrate (mg/L)	0.2 - 0.8	0.0 - 0.3	0.0 - 0.2	0.1 - 0.5	2.1 - 3.1

In addition to clear water with adequate light penetration, nutrients such as phosphate and nitrate are often required to support growth of an algal mat. The Hach 334N and Hach 535P methods for nitrate and phosphate analysis, respectively, were selected as the best suited methods for cursory analysis in the field. However, it was difficult to draw conclusions on nitrate limitation as most of the nitrate values measured were <1 mg/L, whereas the instrument was calibrated with a 20 mg/L standard solution. The nitrate values for the water samples from Denison TMA1 were higher than those

from the other sites, which suggest that nitrogen is probably not a limiting factor for the site. In general nitrate levels of <100 ug/L are limiting for most ecosystems (Sigee, 2005).

As with nitrate, the rapid Hach method selected for the cursory phosphate analysis in the field was not sensitive enough to produce reliable estimates of phosphate levels within the ponds. However, the results suggest that the Nova Scotia pond site has detectable phosphate levels and may not exhibit phosphorous limitation.

More sensitive methods than the Hach 344N and Hach 535P would need to be employed to determine nitrate and phosphate levels in the other tailings ponds with confidence and to draw conclusion on their nutrient status.

In vivo chlorophyll analysis is the measurement of chlorophyll fluorescence within a living cell. The use of the measurement of phytoplankton as an indicator of water quality is described in Standard Methods (APHA, 1992). A frequent water quality problem in lakes and reservoirs is the excessive growth of phytoplankton due to high concentrations of plant nutrients. Water bodies with high nutrient concentrations and low dissolved oxygen levels are classified as eutrophic waters (Kevern et al., 2004). The qualitative chlorophyll-A values obtained in the field would suggest low phytoplankton counts, more typical of oligotrophic systems, i.e. ones with considerable oxygen but a limited nutrient concentration.

Laboratory Analyses

The results of the ICPMS scan and dissolved carbon analyses of the water-cover samples and porewater samples extracted from the sediment cores are presented in full in Appendix B. Variations in selected parameters with depth in each tailings pond are depicted in this section. Salient observations are then described together with pertinent mineralogical data acquired by X-Ray powder diffractometry and scanning electron

microscopy. In addition, microprofiles of pH and dissolved oxygen across the water/tailings interface measured from the collected sediment cores are also provided.

Tailing Impoundment at Louvicourt Mine

Dissolved organic carbon (DOC) as well as most minor and trace elements (including As, Cd, Cu, Fe, Mn, Pb, Sb, Ni, Co and Zn) peak near the water tailings interface (Figure 3), reflecting the accumulation of biomass at the interface and the attenuation of remobilized dissolved metals through sorption with the precipitating ferrihydite. This will be further elaborated in the ensuing discussion. On the other hand, Ag, U and perhaps Th show minimum concentrations at the interface, suggesting that they are being actively removed there. However, as shown by the widely scattered analyses of the water cover at the three sampling locations, this observation may be an artifact of the precision of measurements at near-detection concentrations.

Minerals identified in the tailings sediments include quartz with supporting to minor amounts of illite, feldspars, chlorite, calcite and pyrite. Aggregates of biofilm were also found associated with iron oxyhydroxide upon examination under a scanning electron microscope (Figure 4).

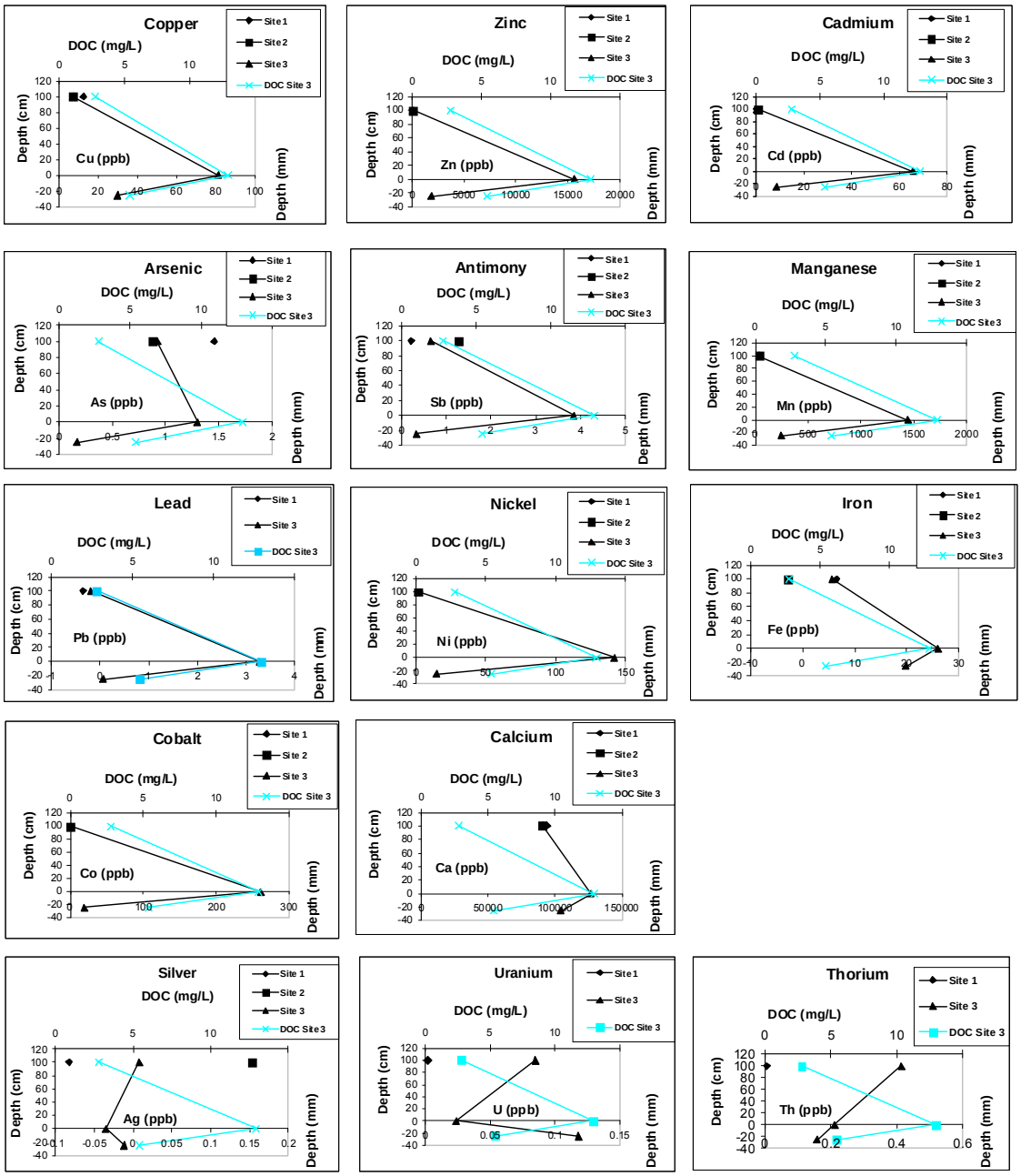

Figure 3 Variation of water chemistry with depth at the Louvicourt tailings pond. (Note that water depth is in cm (+) above the water/tailings interface (0) and in mm (-) below the interface.)

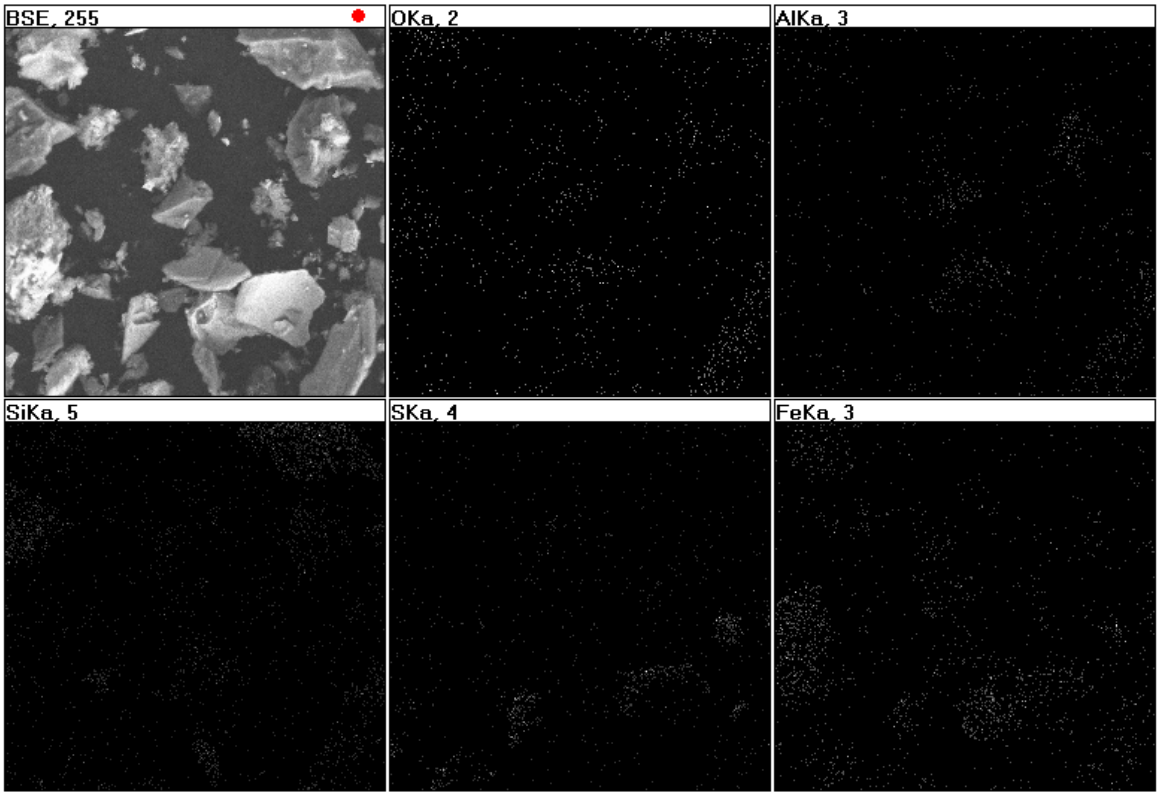

Figure 4 A backscattered electron image (BSE, top left; 1000X magnification) of a subsample of the Louvicourt tailings collected at the water/sediment interface and the corresponding X-Ray maps for O, Al, Si, S and Fe. Bright clusters associated with ferrihydrite (e.g. upper left corner, lower left and near middle of BSE where the X-Rays maps show no S associated with Fe) are biofilm aggregates. The white, platy grain at the lower right corner where Fe and S are found together is pyrite.

Nova Scotia Pond

Only Co, Fe, Mn and perhaps Ca peak at the interface (Figure 5), which indicates redox cycling of Fe and Mn with adsorbed Co. All other elements (including Ag, As, Cd, Cu, Ni, Pb, Sb, Th, U and Zn) show an increase in concentration with depth straight from the overlying water into porewater. This suggests that the submerged tailings are a source rather than a sink of these elements to the surface waters. This is in agreement with the observations of Kwong et al. (2007) at the Farr Creek wetland, located approximately 2 km northwest of the Nova Scotia Mine. The arsenic concentration of the water greatly exceed the Canadian Water Quality Guidelines for the Protection of Aquatic Life of 5 ppb (CCME, 2007) while some other metals, such as Cu and Ni, are

close to the respective guideline values of 2 - 4 and 25 - 150 ppb, depending on water hardness. The tailings pond has been inactive since the 1920s and it was interesting to note fish in the pond: the only site where fish were observed during this study. DOC increases with depth (Figure 5) and shows a good correlation with most of the trace elements (As, Ag, etc.), suggesting possible formation of organic complexes in solution.

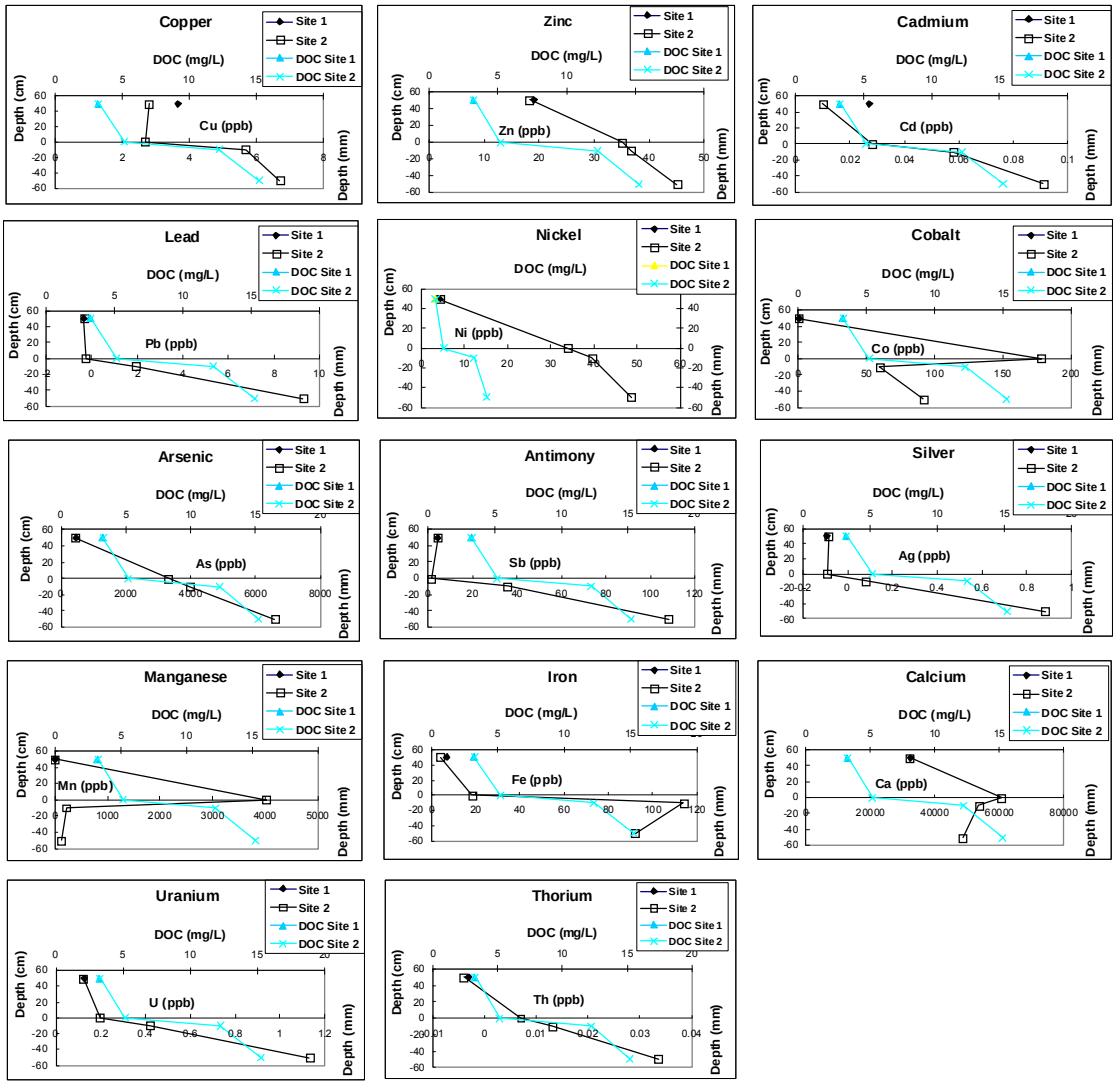

Figure 5 Variation of water chemistry with depth at the Nova Scotia tailings pond. (Note that water depth is in cm (+) above the tailings/water interface (0) and in mm (-) below the interface; insufficient porewater was extracted from the sediment core collected from Site 1 for metals analysis.)

The tailings solids are dominated by quartz, feldspar, chlorite, calcite and minor amounts of amphibole, dolomite and mixed-layer clays. No microbial material or other special features were detected in the SEM examination.

Tailings Pond at Hardy Mine

In the tailings pond of the Hardy Mine, DOC, As, Cd, Sb, Th and Zn concentrations peak at interface while that of U peaks at -2 cm and those of Cu, Fe and Mn at -6 cm below the interface (Figure 6). As will be shown in the ensuing section, the -6 cm depth generally marked a significant reduction or total depletion of dissolved oxygen. The observed variation of water chemistry with depth suggests that the formation of organic complexes generally affects the mobilization and attenuation of As, Cd, Sb, Th and Zn at the Hardy site while reductive dissolution largely controls the mobilization of Fe and Mn and the adsorbed Cu. The reason for the U behavior is unclear but it appears that reduction of the more mobile U^{+6} species into the less soluble U^{+4} species occurs at a less reducing condition than that required for the reduction of Fe^{+3} and Mn^{+4} ions. Overall, however, the dissolved concentrations of most elements are low.

The tailings sediments in the Hardy Mine pond are dominated by feldspars, quartz, chlorite and amphibole. Calcite is locally abundant at intermediate depths. The relative abundance of identified dominant minerals also varies markedly with depth such that any of the minerals can become the dominant phase. It appears that either the tailings are heterogeneous in mineralogical composition or they are mixed to various extents with some original lake sediments.

Oxidation Pond – Onaping Operation

The variation in water chemistry with depth at the oxidation pond (Moose Lake) of the Strathcona Mine is shown in Figure 7. The DOC, Cd, Th and Zn concentrations peak at the tailings/water interface. In contrast, As, Ca, Cu, Fe, Sb and U show concentration minima at the interface and then increase in concentration with depth in the porewater.

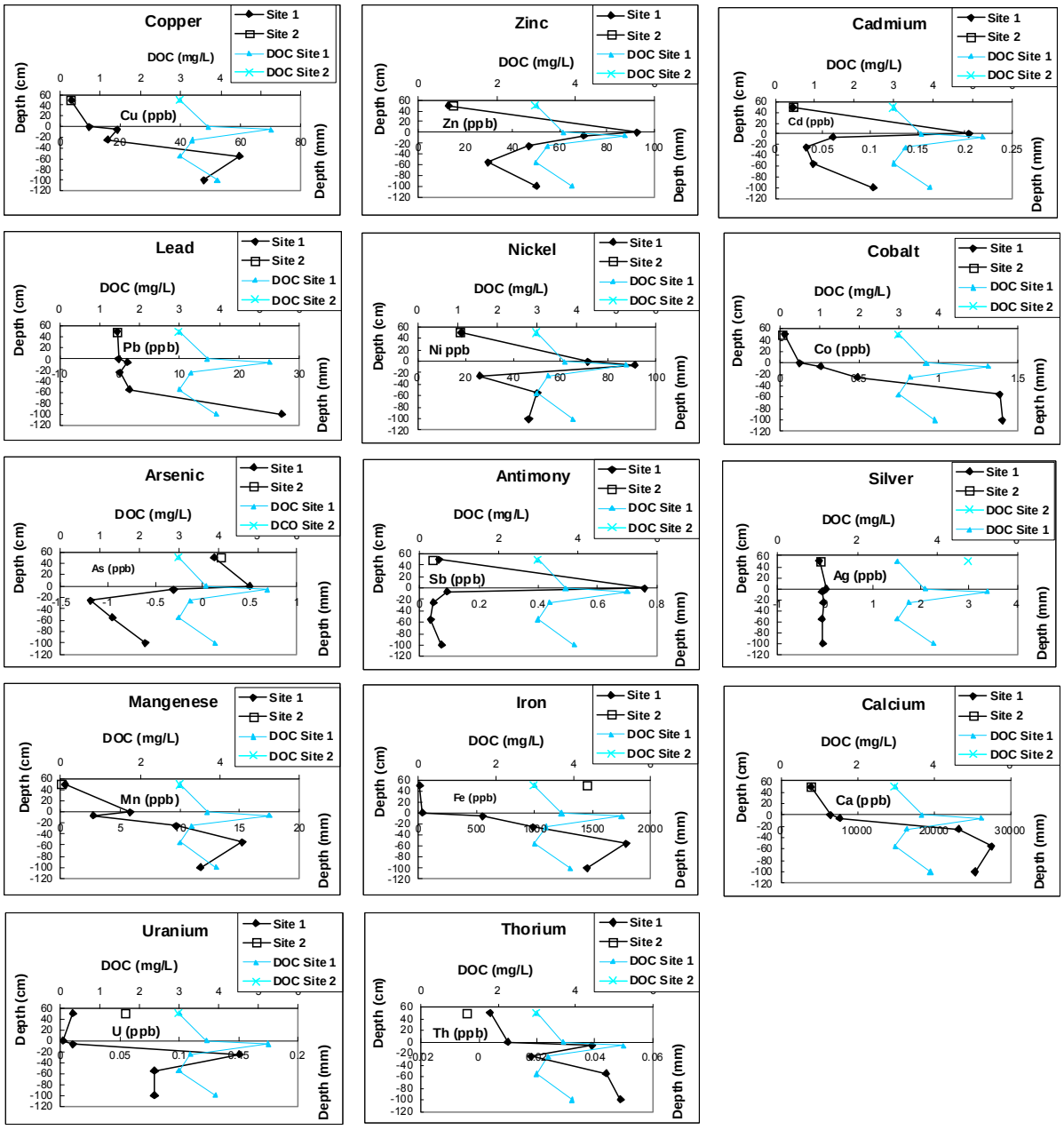

Figure 6 Variation of water chemistry with depth at the Hardy Mine tailings pond. (Note that water depth is in cm (+) above and in mm (-) below the interface (0); insufficient porewater was extracted from Site 2 sediment for metals analysis)

This indicates sorption of the trace elements with Fe-oxyhydroxide precipitated at the interface while the Ca concentration may reflect the effect of lime additions. The Co and Ni concentrations are higher in the water column than in the porewater, where they generally decrease with depth. This suggests that the tailings serve as a sink to these elements in the impoundment.

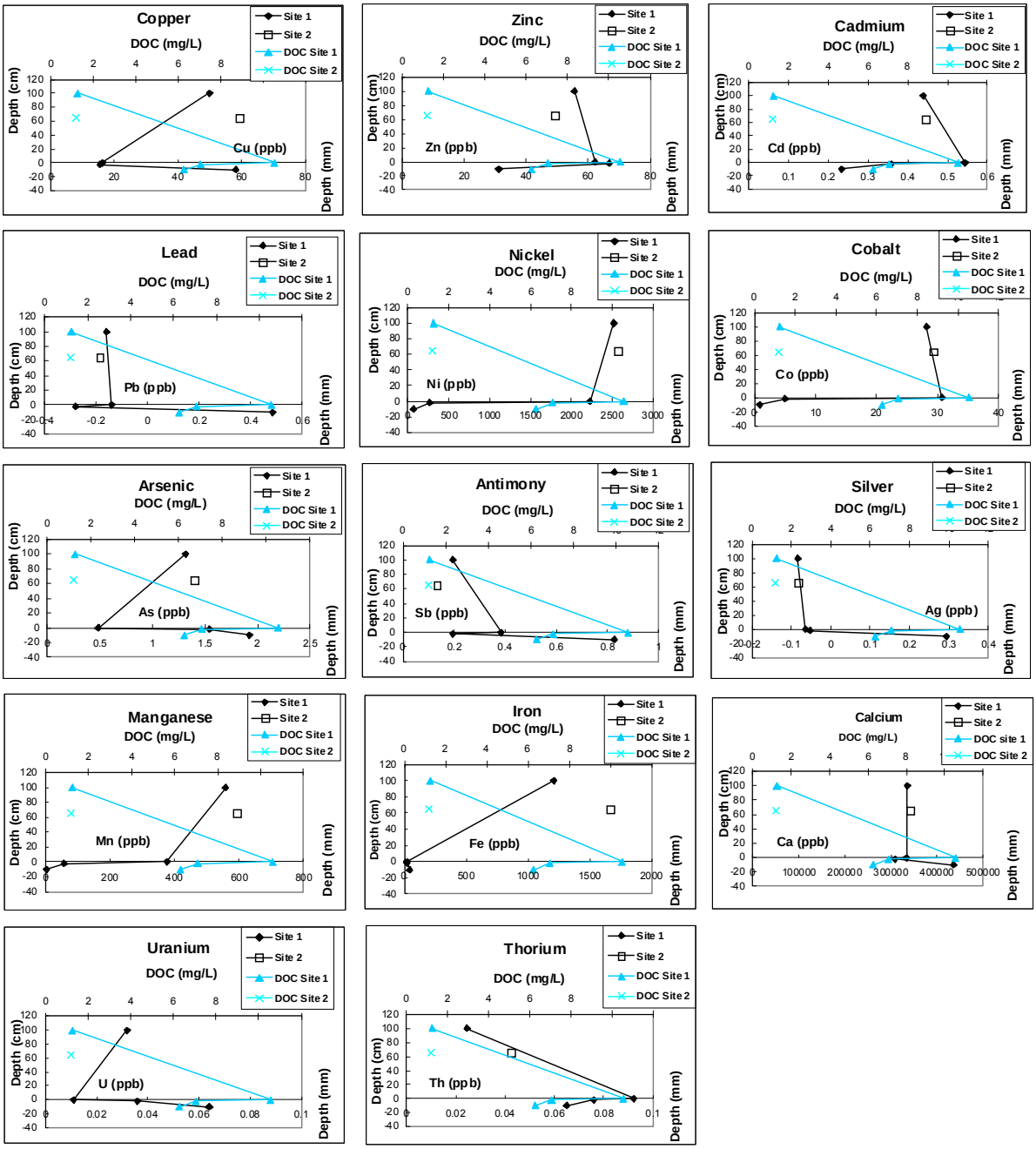

Figure 7 Variation of water chemistry with depth at Moose Lake, Onaping Operation. (Note that water depth is in cm (+) above and in mm (-) below the interface (0); insufficient porewater was extracted from Site 2 sediment for metals analysis)

The concentration of Ag is negligible in the water cover but is detectable and increases with depth in the tailings porewater. This suggests that Ag can be mobilized below the water/tailings interface by forming a soluble complex with organics under reducing conditions. In the overlying water, however, Ag is not present.

Major minerals identified in the oxidation pond tailings by XRD include plagioclase, biotite, amphibole, chlorite, talc, pyrrhotite and minor amounts of quartz and K-feldspar. Similar to the Louvicourt tailings, there are indications of microbial aggregates associated with Fe-oxyhydroxides under SEM examination but the frequency of occurrence is significantly less than that observed in the Louvicourt surface tailings.

TMA1 – Denison Mine

Intact sediment cores could not be secured in the field because of the fluid nature of the submerged tailings. Depth profiles of water chemistry are therefore not available. However, a review of the appended data on the composition of the water cover and porewater (Appendix B) extracted from three bulk sediment samples give rise to the following observations:

1. Except for Ca, Fe, Mg, Mn and perhaps Cr and Zn, most major, minor and trace elements show higher concentrations in the porewater than in the water cover.
2. There are relatively large differences in water column and porewater chemistry in sampling locations less than 50 m apart, suggesting that the water cover is not well mixed.

Major crystalline phases identified by XRD in the tailings sediments from the Denison TMA1 include quartz, illite, pyrite, calcite, feldspars and chlorite. Examination of subsamples of these sediments under a SEM showed evidence of amorphous iron monosulphides associated with microbes (Figures 8 and 9), indicating that active sulphate-reduction is occurring in the TMA. However, whether or not sulphate reduction occurs across the entire impoundment cannot be established by the current cursory field survey and sampling.

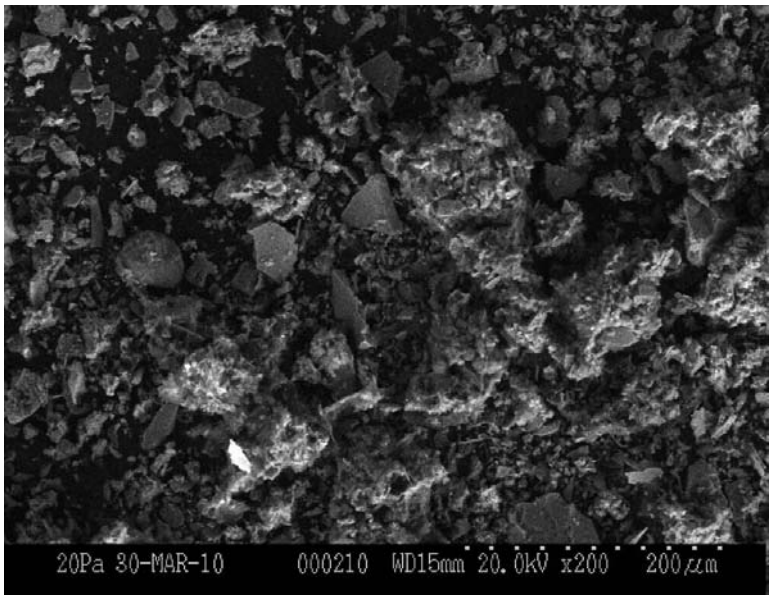

Figure 8 Backscatter electron image of a tailings subsample from the Denison TMA1 at 200X magnification. The bright grain at the lower left is monazite (a rare earth phosphate). The scattered light gray patches covering some larger grains are iron monosulfide and microbes. The gray minerals in the matrix are largely quartz with minor amounts of K-feldspar, mica, calcite and pyrite.

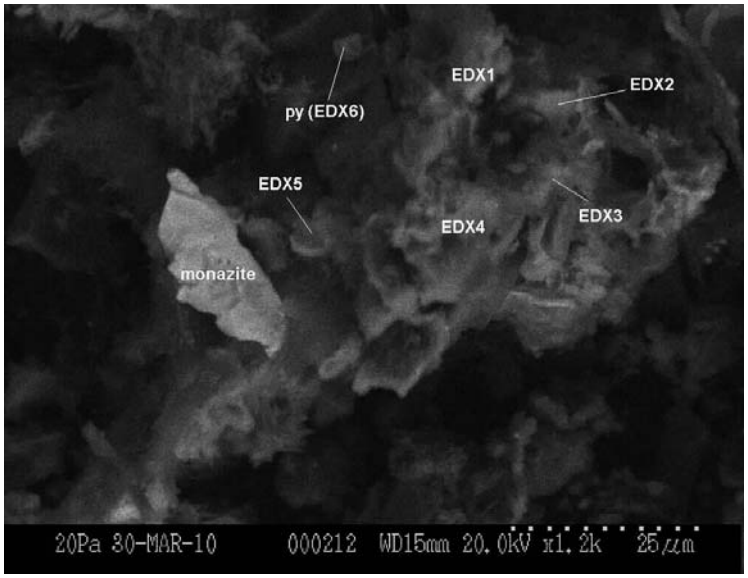

Figure 9 Enlarged (1200X) BSE image of the SW quadrant of Figure 8. *In-situ* spot EDX analyses at locations EDX 1-6 confirm that they are composed of iron monosulphide associated with silica and carbon.

Micro-pH and Dissolved Oxygen Profiles in Selected Sediment Cores

Figures 10 to 12 depict the micro-pH and dissolved oxygen profiles across the water/sediment interface in the intact core samples acquired from the Louvicourt Mine, Hardy Mine and Moose Lake, respectively. Similar profiles are not available for the Nova Scotia and Denison TMA1 submerged tailings because tailings sediments at the former site are too granular for the micro-electrode to penetrate without breaking and no sediment core was acquired from the latter site.

Dissolved oxygen was practically depleted 6 mm below the water/tailings interface at both the Louvicourt tailings impoundment and Moose Lake. At the Louvicourt mine, porewater pH in the tailings decreased with depth until 6 mm below the interface, where it stabilized at pH~5.4. The slight decrease in pH with depth may reflect the presence of organic acid resulting from decay of accumulated organic matter. At Moose Lake, porewater pH showed slight increase with depth once past the 6 mm mark below the interface. This likely reflects reductive dissolution of ferric oxyhydroxide embedded in the submerged tailings, which consumes acid. At the Hardy mine tailings pond, porewater pH showed slight decrease with depth until 6 mm below the interface, where it stabilized at pH 6.9. Dissolved oxygen, on the other hand, was still detectable 15 mm below the interface, possibly reflecting less organic decay or sulphide oxidation at the surface of the submerged tailings.

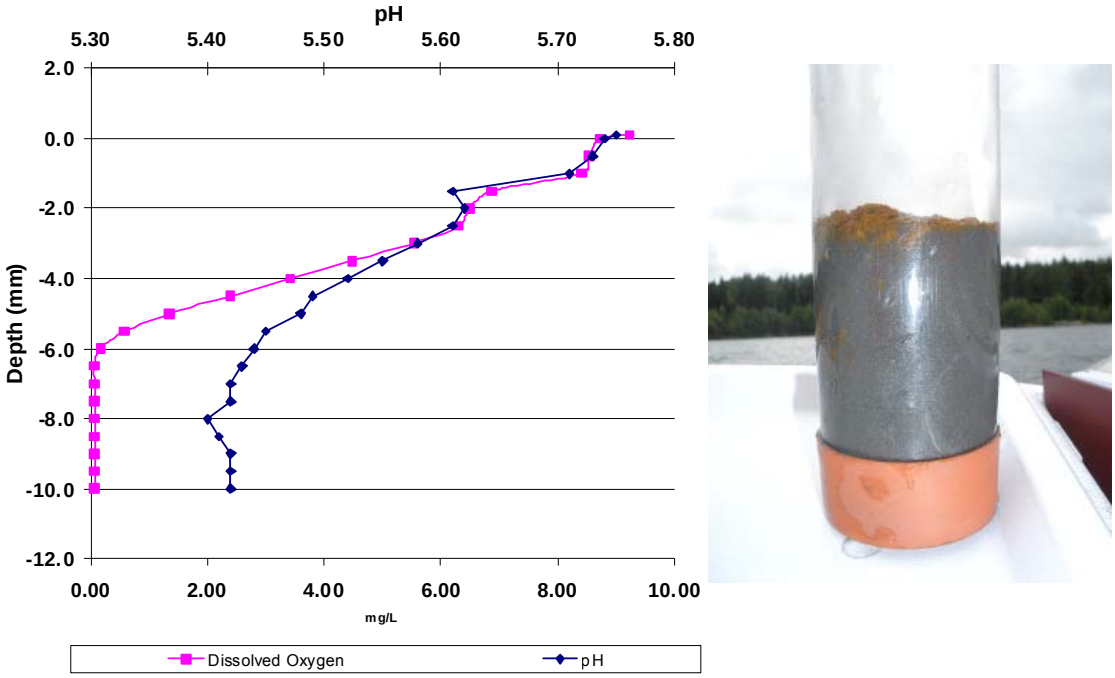

Figure 10 Micro-pH and dissolved oxygen profiles measured in the sediment core from Sampling Site 3 at the Louvicourt Mine.

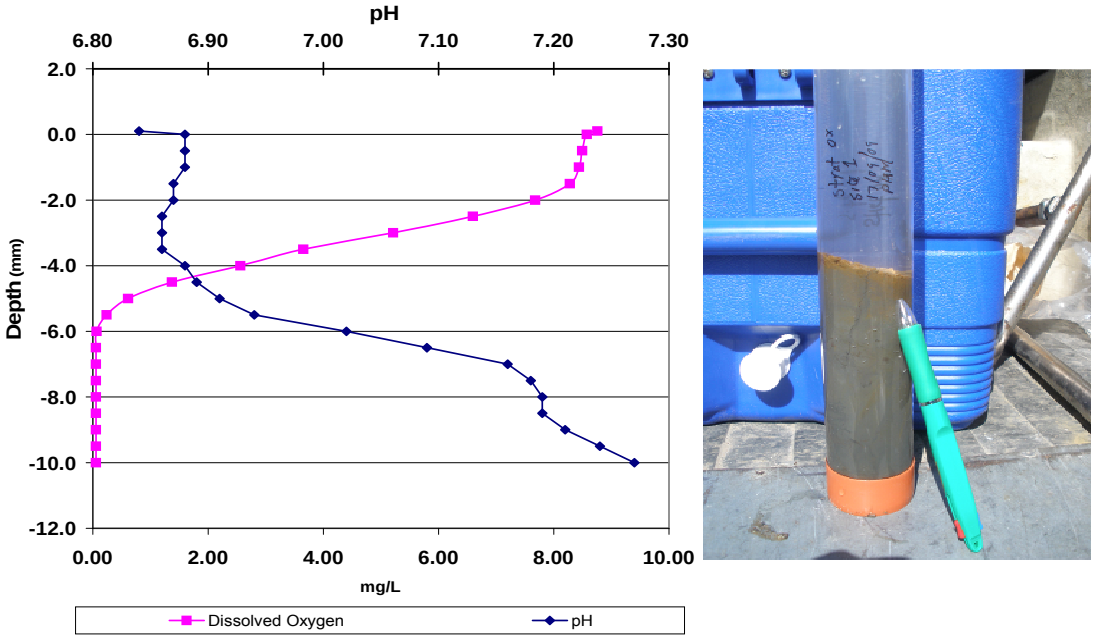

Figure 11 Micro-pH and dissolved oxygen profiles measured in the sediment core from Sampling Site 1 at the Strathcona Mine.

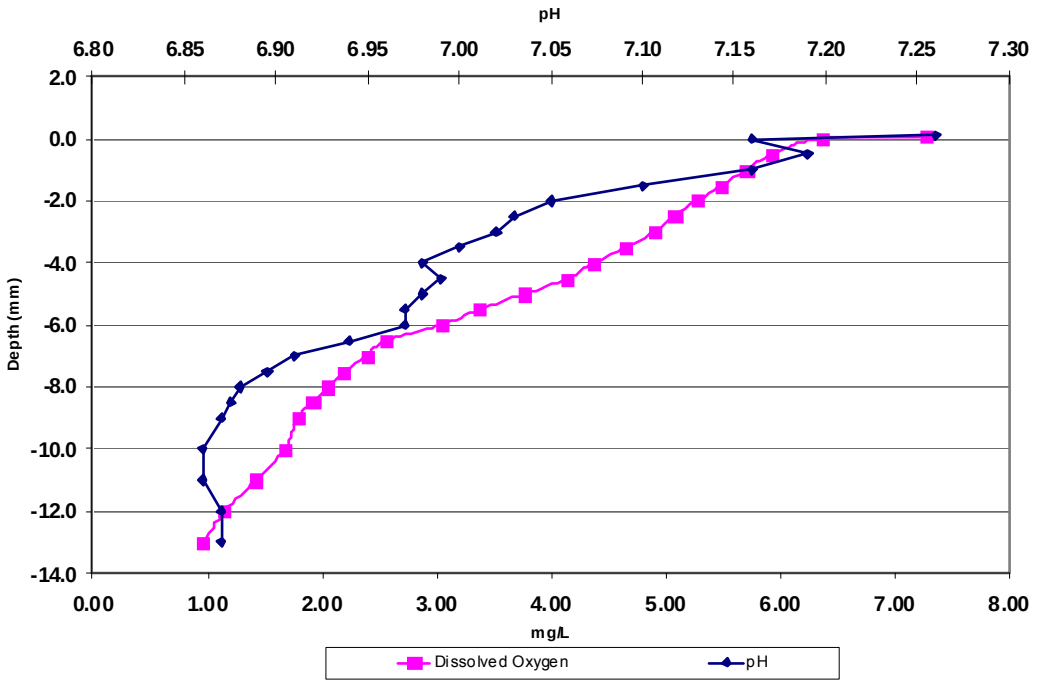

Figure 12 Micro-pH and dissolved oxygen profiles measured in the sediment core from Sampling Site 3 at the Hardy Mine.

DISCUSSION

Possible Reasons for Lack of Algal Microbial Mat at the Tailings Impoundments Examined

The cursory investigation at the five mine sites with tailings of different compositions placed under a water cover indicated that algal biofilm formation over submerged mine tailings is not widespread. Although the observation of isolated microfilms at the Louvicourt and Strathcona tailings impoundments might suggest that a microbial mat was developing, the rate of growth was much lower than that previously observed at the Louvicourt field cells. The growth of higher order plants in the older ponds at the Nova Scotia and Hardy mine ponds may be due to natural succession which started out with some form of microbial mat. However, another interpretation is that the continuous biofilm layer observed by Vigneault et al. (2007) in the former field test cells (decommissioned in 2008) at the Louvicourt Mine was perhaps a rare occurrence

created by an optimum set of specific ecological and physical conditions. A comparison of the environmental settings between the former Louvicourt field cells and the five sites visited for this study suggested that the requirements for the formation of continuous algal biofilm might include the following:

1. A shallow, oxygenated water cover with sufficient light and heat penetration: Compared to the former field cells at the Louvicourt Mine which had a water cover of only 0.3 m (Vigneault et al., 2007), none of the sites examined in this study has a water depth less than 0.5 m. The difference in depth of the water covers may have led to significant reduction in light penetration which is essential for photosynthetic bacteria to flourish. The shallower depth at the Louvicourt field cells likely also translates to a higher average water temperature, particularly in the summer, further stimulating microbial growth.

2. A relatively quiescent environment, i.e., no active tailings movement: At the Moose Lake tailings impoundment of the Strathcona Mine at Onaping, extensive microbial colonization of epilimnetic-associated pyrrhotite was reported by Bernier and Warren (2005). The current work also found evidence of microbes associated with intermediate alteration products of pyrrhotite oxidation. The absence of a continuous microbial mat forming on the submerged tailings could be a consequence of ongoing tailings placement at Moose Lake. In addition, the size of all the tailings impoundments visited is orders of magnitude larger than the former field cells at the Louvicourt Mine, and disturbances due to wind and open water current are likely more severe. This would hamper the formation of continuous algal mats.

3. A suitable substrate for the microbial population to propagate: The algal biofilm at the former Louvicourt field cells was built on precipitating iron oxyhydroxides at the tailings/water interface. The redox cycling of iron near the interface sustains the continual growth of the biofilm layer in a quiescent environment. Although iron oxyhydroxides are actively forming at the Strathcona oxidation pond,

continual disturbance apparently prevents the microbes from aggregating the precipitates to form a mat. The mineralization at the Nova Scotia Mine represents a system relatively impoverished in iron and sulphur which accounts for the lack of iron oxyhydroxides observed on the submerged tailings. For the formation of biofilm under reducing conditions, a readily consumable carbon source (e.g. decaying organic matter) is required to sustain microbial growth. Whereas the dissolved organic carbon content at all the five sites examined is of the same order of magnitude, it is not known if the dissolved carbon occurs as simple organic compounds or refractory humic substances. The former is apparently lacking at both the Nova Scotia Mine and Hardy Mine sites such that no slimy biomass was found associated with the submerged tailings. In any case, as observed at the Denison TMA1, the slimy deposits resulted from sulphate reduction formed readily segregated masses, rather than a continuous mat. In addition, at the Nova Scotia Mine it is not clear if the lack of vegetation decay, which is the primary source of consumable carbon, is due to the high dissolved arsenic content in the pond.

While the Louvicourt, Strathcona and Denison sites are either operating or recently closed mines, both the Nova Scotia and Hardy Mines are historic mines (50-90 years old). At these two historic sites only aquatic weeds were observed. The reason for the absence of biofilm is not known. Aging may have brought about a transition from algae dominance to the development of aquatic weeds at these two sites.

Limitations of the Current Investigation and Suggested Improvements for Future Field Work

Although there was no evidence of extensive biofilm layers in any of the five tailings impoundments surveyed, the effectiveness of microbes in sequestering metals and attenuating their aqueous transport is well documented (e.g. Lawrence et al., 1998; Haack and Warren, 2003; Vigneault et al., 2007). Potential benefits of biofilm formation may include improved performance of shallow water covers, and perhaps an elimination of more expensive deeper covers. It is thus fruitful to further research their occurrence,

functions and behavior in various mine site settings. The current field study is limited in that only a very small portion of the entire tailings impoundment was surveyed at each site. Thus, it cannot be confirmed if biofilm formation prevailed in other parts of the impoundments. In hind sight, given the size of the impoundments at all the five sites, the use of a motor boat to navigate across the ponds would not significantly disturb the underlying tailings. If a motor boat is utilized, a better scheme for surveying for biofilm formation could be used, as follows:

1. set up a surveying grid over the entire impoundment;
2. collect under-water video and log depth using a bathymeter as the boat travels along the grid lines;
3. mark locations of interest for sampling while running the grid line; and,
4. complete field program by detailed water and tailings profiling and sampling at the selected locations

Mine site personnel could perform a preliminary visual survey to determine the existence of biofilm on the submerged tailings on their site. Cursory surveys could then be conducted at ten to twelve mine sites with submerged tailings located across the country. This could be followed up with a detailed study at four to six selected sites with different tailings composition and environmental settings to unequivocally establish the conditions required for the formation of continuous algal biofilms on submerged tailings. At a minimum, the detailed investigation should include the items described by Vigneault et al. (2007); i.e., detailed solids characterization, water chemistry profiling across the tailings/water interface, speciation of the microbial population, etc. It is only through a thorough understanding of the tailings-microbe interactions and the conditions required for the propagation of the most suitable community of microbes that a new technology can be developed to take advantage of microbes to better manage mine waste, from both an economic and environmental perspective.

CONCLUSIONS

Based on the cursory field survey at five sites practicing under-water tailings disposal along with subsequent laboratory analyses and literature research, the following conclusions can be drawn:

1. As no extensive microbial mat was found in any of the five sites investigated, its formation over submerged tailings does not appear to be a common phenomenon.

2. The formation of a continuous biofilm layer previously observed at the field test cells of the Louvicourt Mine is probably the product of a specific combination of ecological settings, including a shallow depth with ample light penetration and a quiescent environment.

3. Until further studies reveal the presence of continuous microbial mats over submerged tailings at Canadian mine sites and the physico-chemical or ecological constraints on the establishment of continuous biofilm are better defined, it is premature to develop new technologies to encourage biofilm formation over submerged tailings, despite its beneficial effects.

4. As microbes are known to affect sulphide oxidation as well as transport and attenuation of trace elements, further research on detailed characterization of microbes and their biogeochemical roles under both acidic and neutral conditions is recommended for developing sustainable strategies in managing submerged mine wastes.

ACKNOWLEDGEMENTS

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APPENDIX A -

Google Maps Showing Site and Sampling Locations

Figure A-1 Location and size of the tailings impoundment and sampling sites at the Louvicourt Mine.

Figure A-2 Location of pond containing tailings and the sampling sites at the Nova Scotia Mine.

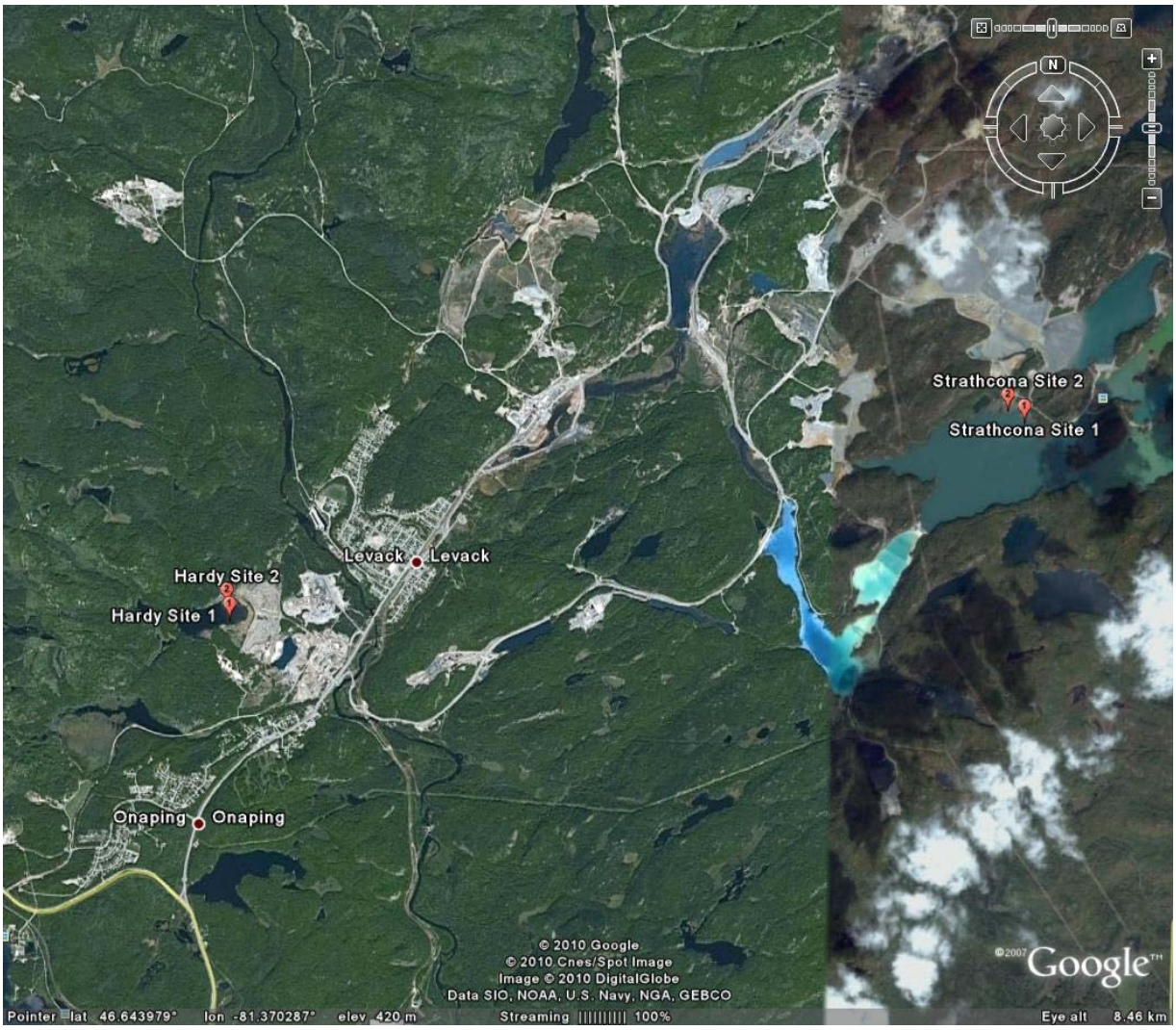

Figure A-3 Location of the Strathcona and Hardy Mines.

Figure A-4 Location of the oxidation pond (Moose Lake) and sampling sites at the Strathcona Mine.

Figure A-5 Size of the tailings pond and sampling sites at the Hardy Mine.

Figure A-6 Location the tailings impoundment TMA1 and sampling sites at the Denison Mine.

APPENDIX B -

Analytical Results

Sample Code Description

Sample ID	Description
SO-S1A	Strathcona Oxidation Pond Site 1
SO-S1A-dup	Strathcona Oxidation Pond Site 1 (ASG Duplicate)
SO-S2A	Strathcona Oxidation Pond Site 2
SO-S2BA	Strathcona Oxidation Pond Site 2B (Field Duplicate)
HA-S1A	Hardy Site 1
HA-S2A	Hardy Site 2
DE-S1A	Denison Site 1
DE-S2A	Denison Site 2
DE-FBA	Denison (Field Blank)
NS-S1A	Nova Scotia Site 1
NS-S2A	Nova Scotia Site 2
NS-S2BA	Nova Scotia Site 2 (Field Duplicate)
NS-FBA	Nova Scotia (Field Blank)
L-S1A	Louvicourt Site 1
L-S2A	Louvicourt Site 2
L-S2BA	Louvicourt Site 2 (Field Duplicate)
L-S3A	Louvicourt Site 3
L-FBA	Louvicourt (Field Blank)
Pore water from Core samples separated in lab	
L3-SW	Louvicourt Site 3 Surface Water from Core sample
L3-0-5	Louvicourt Site 3 Pour water 0 - 5 cm segment
SOX1-SW	Strathcona Oxidation Pond site 1 surface water from Core
SOX1-0-4	Strathcona Oxidation Pond site 1 Pore water 0 - 4 cm segment
SOX1-6+	Strathcona Oxidation Pond site 1 Pore water > 6 cm segment
HS1-SW	Hardy Site 1 Surface Water from Core Sample
HS1-0-12	Hardy Site 1 Pore water 0 - 12 cm segment
HS1-12-40	Hardy Site 1 Pore water 12 - 40 cm segment
HS1-40-70	Hardy Site 1 Pore water 40 - 70 cm segment
HS1-70+	Hardy Site 1 Pore water > 70 cm segment
NSS2-SW	Nova Scotia Site 2 Surface Water from Core
NSS2-0-20	Nova Scotia Site 2 Pore water 0 - 20 cm segment
NSS2-20-80	Nova Scotia Site 2 Pore water 20 - 80 cm segment
NSS2-20-80-dup	Nova Scotia Site 2 Pore water 20 - 80 cm segment (ASG Duplicate)

Shaded Area - Samples obtained from core samples collected.

Table B1-1 ICPMS scan of selected elements. (Note that these analyses are considered as semi-quantitative for sample comparison only.)

	Element	Li	Be	Na	Mg	Al	K	Ca	V	Cr	Mn	Fe	Co	Ni	Cu
	Unit	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
	Blank	0	0	0.197	0	0	0.168	0.008	0	0	0	0.027	0	0	0
	External standard	200.5	200.3	201.6	200.8	201	201.8	201	201.1	201	200.8	200.9	201	200.9	200.9
	TM-28.3	3.443	3.584	5597	3500	44.09	610.8	15130	2.583	4.071	5.708	14.28	2.921	9.902	6.48
	TMDW	16.93	20.76	5653	9248	124.2	2492	38450	26.08	17.37	34.67	112.5	21.09	60.56	19.77
SO-S1A	184967-1	13.01	0.086	95420	43850	56.95	25560	334300	0.447	0.226	557.4	1214	28.27	2515	50.08
SO-S1A-dup	184967-2	12.96	0.076	95540	44050	56.77	25430	336100	0.604	0.294	557.8	1205	28.1	2510	49.71
SO-S2A	184968	13.32	0.238	96980	44170	81.56	25700	339700	0.708	0.274	589.6	1665	29.61	2576	59.51
SO-S2BA	184969	12.88	0.095	96700	44880	86.39	25830	341500	0.628	0.202	593.9	1666	29.16	2576	59.48
HA-S1A	184970	0.264	0.012	937	1377	4.56	288.2	3995	0.205	0.048	0.372	9.342	0.028	18.43	3.812
HA-S2A	184971	0.186	-0.004	871.8	1349	4.673	273.7	3866	0.187	0.043	0.224	7.829	0.015	17.69	3.598
DE-S1A	184972	6.642	0.024	2947	3749	20.85	3426	85240	0.197	0.066	0.919	11.3	0.183	3.195	1.388
DE-S2A	184973	6.748	-0.003	2939	3697	21.29	3403	84800	0.186	0.09	0.781	12.04	0.165	2.112	1.424
DE-FBA	184974	0.027	0.002	3.811	4.196	4.585	-8.836	17.74	0.176	0.092	0.085	9.821	0.005	1.214	2.794
NS-S1A	184975	1.506	0.013	1538	8881	3.786	996.2	32400	0.319	0.202	0.394	6.904	0.438	4.226	3.673
NS-S2A	184976	1.541	0.018	1537	8821	4.06	990.6	32030	0.347	0.109	0.313	2.794	0.345	4.268	3.082
NS-S2BA	184977	1.513	-0.009	1501	8797	3.191	983.7	32330	0.367	0.156	0.397	5.103	0.358	4.321	2.521
NS-FBA	184978	0.029	0.008	30.21	10.38	4.734	-2.784	37.74	0.181	0.034	0.294	2.001	0.01	1.161	7.217
L-S1A	184979	1.691	0.025	7602	9068	3.814	4571	94260	0.206	0.098	37.45	6.574	0.145	1.936	12.58
L-S2A	184980	2.202	0.02	7935	9234	8.96	4944	95830	0.226	0.265	44.66	27.02	0.216	1.957	13.35
	Rinse	-0.002	-0.001	1.612	0.544	-0.012	2.371	7.095	-0.001	0.003	-0.018	0.635	0	0.01	0.013
	Blank	0	0	0.047	0.001	0	0.059	0.021	0	0	0	0.052	0	0	0
	External	200.7	200.7	201.1	200.8	200.8	201.1	201	201	201	200.9	201.2	201	201	201
	Rinse	0.131	0.006	1.161	-0.025	-0.019	0.341	1.893	0.006	-0.004	-0.018	-1.549	0.003	0.009	0.014
L-S2BA	184981	2.399	0.326	7445	8697	6.635	4367	90290	0.363	0.211	36.17	-2.704	0.34	1.893	7.165
L-S3A	184982	2.007	0.111	7481	8812	5.092	4441	90970	0.237	0.166	36.17	5.708	0.195	1.916	7.13
L-FBA	184983	0.046	0.117	-19.55	4.284	-1.08	-186.1	-32.37	0.076	-0.398	0.482	-133.2	0.177	0.162	0.081
L3-SW	184984	7.852	0.044	9009	18710	17.13	5889	126800	0.307	0.424	1447	25.95	260.8	141.9	81.4
L3-0-5	184985	5.865	0.079	9104	12330	3.402	4785	104100	0.276	0.227	241.8	19.82	18.9	15	29.86
SOX1-SW	184986	12.57	0.005	113000	54340	7.414	38520	333200	0.536	0.341	377	21.43	30.77	2227	16.23
SOX1-0-4	184987	8.398	0.01	111800	116600	9.449	39680	308400	0.61	0.278	56.92	21.35	5.006	264.3	15.38
SOX1-6+	184988	19.64	0.068	115400	51520	15.07	48480	436100	1.221	0.571	3.435	44.72	0.84	70.31	58.29
HS1-SW	184989	0.972	-0.024	1418	2257	3.685	932.7	6490	0.218	0.29	5.845	32.01	0.124	71.3	9.844
HS1-0-12	184990	0.329	-0.013	1260	2666	108.8	686.7	7709	0.3	0.946	2.736	548.9	0.259	90.95	18.97
HS1-12-40	184991	0.399	0.021	1075	2755	120.8	377.1	23240	0.291	0.314	9.691	986.8	0.491	26.03	15.83
HS1-40-70	184992	0.519	0.067	1100	2153	501.4	732.9	27550	0.518	0.966	15.23	1788	1.384	50.06	59.58
HS1-70+	184993	0.645	0.022	1182	2162	548.1	814	25410	0.535	1.004	11.73	1454	1.404	46.53	47.78
NSS2-SW	184994	2.807	0.042	2529	10440	4.346	1597	60630	0.225	0.289	4022	18.4	178.3	34.04	2.679
NSS2-0-20	184995	3.953	0.005	2983	7828	12.64	3623	53590	0.624	0.536	218	113.8	59.33	39.59	5.679
NSS2-20-80	184996-1	8.684	0.022	4477	9097	125.7	2971	48700	0.754	0.278	114.4	92.76	91.72	48.29	6.628
NSS2-20-80-dup	184996-2	8.976	0.029	4542	9196	123.4	2989	48750	0.764	0.318	114.4	91.16	91.42	48.97	6.792
	Element	Zn	As	Se	Rb	Sr	Mo	Ag	Cd	Sb	Ba	Pb	Bi	Th	U
	Sample	0.041	0.03	0.143	0.009	0.013	0.009	0.059	0.002	0.003	0.001	-0.006	-0.001	-0.001	0.001
	Unit	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
	Blank	-0.001	0	-0.001	0	0	0	0	0	0	0	0	0	0	0
	External standard	200.8	200.8	200.6	200.7	200.6	200.6	200.7	200.4	200.6	200.3	199.9	200	103.6	200.1
	Rinse	0.057	0.037	0.045	0.031	0	0.203	0.03	0.008	0.344	0.006	0.005	0.303	0.044	0.024
	TM-28.3	32.16	6.762	5.551	0.378	72.87	3.939	2.954	1.973	3.037	15.18	3.222	1.437	0.032	4.789
	TMDW	77.29	79.9	10.74	8.546	263.6	103.7	16.37	10.02	8.77	48.97	36.65	8.065	0.084	8
	Rinse	0.086	-0.005	-0.001	0.008	0.002	0.14	0.015	0.005	0.052	0.004	-0.002	0.05	0	0.005
SO-S1A	184967-1	55.59	1.315	6.842	31.03	1486	0.709	-0.107	0.408	0.252	46.66	-0.16	0.381	0.025	0.033
SO-S1A-dup	184967-2	55.75	1.314	6.726	31.54	1510	0.56	-0.059	0.469	0.137	47.73	-0.158	0.173	0.024	0.031
SO-S2A	184968	49.52	1.414	6.395	31.64	1518	0.491	-0.044	0.515	0.183	47.17	-0.098	0.223	0.075	0.14
SO-S2BA	184969	48.8	1.392	6.904	31.48	1525	0.32	-0.119	0.378	0.084	47.34	-0.274	0.078	0.01	0.038
HA-S1A	184970	12.63	0.124	-0.421	1.101	15.07	0.133	-0.121	0.018	0.065	13.32	-0.396	0.08	0.004	0.01
HA-S2A	184971	14.29	0.199	0.183	1.116	14.56	0.065	-0.109	0.019	0.042	9.785	-0.398	0.016	-0.004	0.054
DE-S1A	184972	11.53	1.744	-0.31	11.03	66.65	0.842	-0.11	0.017	0.047	34.95	-0.399	0.006	0.004	25.19
DE-S2A	184973	9.508	1.839	0.613	10.97	65.82	0.728	-0.105	0.013	0.091	34.38	-0.405	0.005	0.003	24.52
DE-FBA	184974	8.043	0.16	0.234	-0.03	0.024	0.033	-0.091	0.008	-0.006	1.294	-0.353	0.006	-0.004	0.02
NS-S1A	184975	19.05	460	0.507	2.069	31.59	1.365	-0.093	0.027	4.327	10.66	-0.341	0.006	-0.003	0.128
NS-S2A	184976	20.25	451.7	0.86	2.046	31.3	1.399	-0.097	0.018	4.185	10.14	-0.385	-0.002	-0.004	0.13
NS-S2BA	184977	16.1	456.2	-0.364	2.028	31.34	1.323	-0.075	0.002	4.286	7.968	-0.327	-0.007	-0.004	0.113
NS-FBA	184978	27.64	0.012	-0.718	0.017	0.341	0.021	-0.094	0.03	0.002	7.915	-0.308	-0.003	-0.013	0.002
L-S1A	184979	119.7	1.455	2.563	2.522	166.1	0.271	-0.082	0.262	0.212	9.801	-0.352	-0.003	0.006	0.002
L-S2A	184980	126.8	0.812	1.234	3.852	255	0.492	-0.057	0.252	0.225	11	-0.031	0.009	0.005	0.001
	Rinse	0.08	-0.007	-0.051	0.002	0.02	0	0.018	0.002	0.002	0.001	-0.004	0	-0.001	0
	Blank	0.001	-0.003	0	0	0	0	0	0	0	0	0	0	0	0
	External	200.8	200.8	200.7	201	200.9	200.9	200.9	200.7	200.6	200.7	200.8	200.7	200.6	200.5
	Rinse	0.041	0.015	-0.012	0.021	0.004	0.208	0.043	0.003	0.366	0.004	0.005	0.33	0.104	0.022
L-S2BA	184981	117.7	0.874	1.079	2.816	161.7	0.962	0.153	0.527	1.266	12.04	-0.034	1.544	0.978	0.292
L-S3A	184982	118.1	0.923	1.507	2.668	161.1	0.64	0.008	0.352	0.652	11.91	-0.189	0.578	0.414	0.085
L-FBA	184983	-1.414	-0.123	0.5	0.208	0.373	0.185	-0.001	0.108	0.155	0.142	-0.348	0.176	0.211	0.104
L3-SW	184984	15620	1.3	2.95	3.219	234.8	0.385	-0.035	65.67	3.849	40.73	3.266	0.301	0.211	0.024
L3-0-5	184985	1882	0.167	2.059	2.288	184	0.163	-0.011	8.385	0.33	36.84	0.07	0.158	0.157	0.118
SOX1-SW	184986	62.22	0.48	4.597	56.27	1448	6.695	-0.064	0.544	0.384	46.84	-0.141	0.052	0.092	0.011
SOX1-0-4	184987	66.69	1.544	5.225	62.85	1309	79.61	-0.052	0.358	0.194	23.8	-0.28	0.039	0.076	0.036
SOX1-6+	184988	31.13	1.923	36.69	159.7	1935	99.31	0.294	0.233	0.827	39.46	0.485	0.052	0.065	0.064
HS1-SW	184989	92.59	0.497	0.391	1.553	21.5	0.468	0.008	0.204	0.758	26.36	-0.231	0.006	0.01	0.002
HS1-0-12	184990	70.02	-0.307	0.634	1.76	24.83	0.284	-0.063	0.061	0.093	17.56	1.308	0.011	0.039	0.01
HS1-12-40	184991	47.03	-1.186	-0.333	1.299	28.52	0.129	-0.041	0.033	0.047	7.551	0.031	0.004	0.018	0.151
HS1-40-70	184992	29.55	-0.955	0.072	1.588	31.41	0.095	-0.071	0.04	0.037	6.104	1.626	0.017	0.044	0.079
HS1-70+	184993	50.08	-0.609	0.403	2.119	33.18	0.049	-0.054	0.103	0.074	9.499	26.98	0.01	0.049	0.079
NSS2-SW	184994	35.14	3310	-0.166	3.975	53.71	1.91	-0.09	0.028	1.299	59.31	-0.263	-0.012	0.007	0.198
NSS2-0-20	184995	36.72	3982	-0.593	11.67	51.75	2.887	0.081	0.058	35.81	63.95	1.935	0.21	0.013	0.421
NSS2-20-80	184996-1	45.47	6725	0.141	7.92	52.55	6.017	0.834	0.113	108.3	26.16	9.233	0.783	0.022	1.128
NSS2-20-80-dup	184996-2	44.69	6460	-0.149	7.89	52.66	6.181	0.932	0.069	108.5	25.91	9.338	0.799	0.045	1.134

Table B-1-2 Chlorophyll, nutrients and carbon analyses

	Chlorophyl A ug/L	NO3 mg/L	PO43- mg/L	DOC mg/L	TC mg/L	DIC mg/L
Louvicourt						
Site 1	2.2	2.1	0.05	2.736	4.151	1.415
Site 2	1.76	2	0.06	2.788	4.065	1.277
Site 2b	1.8	3.3	0.07	2.703	4.057	1.354
Site 3	1.46	2.4	0.07	2.793	4.313	1.520
Field blank	-0.19	1.9	0.06	1.87	2.79	0.920
Nova Scotia						
Site 1	1.2	1.7	0.27	3.222	19.18	15.958
Site 2	0.76	1.1	0.35	3.281	20.8	17.519
Site 2b	0.8	1.4	0.34	3.252	21	17.748
Field blank	-0.17	1.4	0.09	1.246	2.663	1.417
Hardy						
Site 1	0.93	1.4	0.11	2.994	5.404	2.410
Site 2	0.84	1.9	0.08	2.976	5.38	2.404
Strat						
Site 1	0.09	1.8	0.17	1.249	2.299	1.050
Site 2	-0.15	2.6	0.1	1.202	2.179	0.977
Site 2b	-0.15	1.7	0.21	1.195	2.173	0.978
Denison						
Site 1	0.4	5	0.08	4.447	9.657	5.210
Site 2	0.39	4	0.08	4.401	9.605	5.204
Field blank	-0.15	1.9	0.09	1.325	2.279	0.954