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Environnement Canada

Fate and Transport of Metals from an Abandoned
Tailings Impoundment after 70 Years of Sulfide
Oxidation

By:

M. Moncur, C. Ptacek, D. Blowes, J. Jambor

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Abstract

Hydrogeological and geochemical studies of an abandoned high-sulfide tailings impoundment at Sherridon, Manitoba, were conducted during the summers of 2000 and 2001. The Sherridon tailings have undergone oxidation for more than 70 years. Mineralogical analysis indicates that the unoxidized tailings contain nearly equal proportions of pyrite and pyrrhotite that together make up to 60 wt.% of the tailings. Sulfides are extensively depleted in the upper few centimeters of the tailings. Sulfide oxidation has led to very high concentrations of dissolved iron and sulfate, elevated concentrations of trace metals, and the generation of low-pH conditions. Extensive accumulations of secondary melanterite, rozenite, jarosite, goethite, and gypsum have formed a massive continuous hardpan approximately 1 m below the tailings surface. The highest concentrations of dissolved metals are observed directly above and within the massive hardpan layer. During rainfall or other precipitation events, surface seeps along the flanks of the tailings develop and discharge pore water that has a geochemical composition resembling that of the water directly above the hardpan. These results suggest that shallow lateral flow of water due to a transient perched water table is resulting in higher contaminant loadings than are predicted by assuming that discharge is derived only from the much deeper primary water table. Groundwater and surface water from the tailings flow directly into a small lake adjacent to the impoundment. Samples from the water column of the lake show an abrupt increase in the metal concentrations at a 2-m depth, suggesting that higher density metal-laden water is accumulating at depth. Although the tailings have oxidized for >70 years, the presence of a significant amount of residual sulfide minerals suggests that metals and acid will be released for decades to centuries.

NWRI RESEARCH SUMMARY

Plain language title
Release of metals from old abandoned mine sites

What is the problem and what do sicentists already know about it?
Metals and acid continue to be released from old mine sites for decades, centuries or longer after cessation of mining activities. The duration of release varies from mine site to mine site. Information on how long unacceptable concentrations of metals will be released is available for a few mines in the world, however, there is only limited information for mine sites in Canada.

Why did NWRI do this study?
Elevated concentrations of metals are being released from old mine sites in Manitoba. These sites represent some of the oldest sites where tailings were produced. Tailings are finely-ground wastes. Exposure of these wastes to atmospheric oxygen leads to oxidation and release of metals. NWRI selected the old sites in Manitoba because they provide a picture of what will happen to newer sites elsewhere in Canada.

What were the results?
Seventy years of continuous oxidation has lead to the development of extremely high concentrations of metals and acid in the tailings pore waters. The concentrations observed are much higher than those observed in newer mine sites, and may provide a glimpse of what can be expected at other sites as they age. The pore waters are flowing out of the tailings into a nearby lake. Dense pools of metal-laden water are forming at the bottom of the lake. Elevated concentrations of metals are discharging from the lake into an important local fishery.

How will these results be used?
The results will be used to assist in the design of a remedial system for the site.

Who were our main partners in the study?
Manitoba Mines Branch; Manitoba Conservation; University of Waterloo; University of British Columbia

Transport et état final des métaux provenant d'un bassin abandonné d'accumulation de résidus, après 70 ans d'oxydation des sulfures

M.C. Moncur, C.J. Ptacek, D.W. Blowes et J.L. Jambor

Résumé

Au cours des étés 2000 et 2001, des études hydrogéologiques et géochimiques ont été effectuées dans un bassin abandonné d'accumulation de résidus à forte teneur en sulfures, à Sherridon, au Manitoba. Les résidus ont subi l'oxydation pendant une période de plus de 70 ans. Les résultats de l'analyse minéralogique indiquent que les résidus non oxydés contiennent des proportions presque identiques de pyrite et de pyrrhotite; ces deux minéraux constituent jusqu'à 60 % en masse des résidus. La teneur en sulfures est très faible dans les premiers centimètres des résidus. L'oxydation des sulfures a entraîné des concentrations très élevées de fer et de sulfates dissous, un accroissement de la teneur en métaux traces et des conditions de bas pH. D'importantes accumulations de minéraux secondaires comme la mélantérite, la rozénite, la jarosite, la goethite et le gypse ont provoqué la formation d'une carapace continue massive située à environ 1 m de profondeur. Les concentrations les plus élevées de métaux dissous sont observées dans la carapace massive et directement au-dessus de cette couche. Les chutes de pluie ou autres événements de précipitation provoquent des infiltrations de surface sur les côtés des amas de résidus, ce qui entraîne l'évacuation d'eau interstitielle dont la composition géochimique est semblable à celle de l'eau située directement au-dessus de la carapace. Ces résultats semblent indiquer que l'écoulement latéral et peu profond de l'eau, causé par la surface perchée transitoire de la nappe phréatique, entraîne des concentrations de contaminants plus élevées que celles prévues dans l'hypothèse d'une évacuation qui proviendrait uniquement de la zone primaire, beaucoup plus profonde, de la nappe phréatique. Les eaux souterraines et les eaux de surface provenant des résidus s'écoulent directement dans un petit lac adjacent au bassin d'accumulation. L'analyse des échantillons prélevés dans la colonne d'eau du lac indique qu'il y a une brusque augmentation des concentrations de métaux à une profondeur de 2 m, ce qui pourrait être expliqué par l'accumulation, à une certaine profondeur, de zones très denses d'eau à très forte teneur en métaux. Bien que l'oxydation des résidus se poursuive depuis plus de 70 ans, la présence de quantités importantes de minéraux sulfurés résiduels semble indiquer que le rejet de métaux et d'acide se poursuivra encore pendant des décennies, voire des siècles.

Sommaire des recherches de l'INRE

Titre en langage clair
Rejet de métaux dans des sites miniers abandonnés.

Quel est le problème et que savent les chercheurs à ce sujet?

Le rejet de métaux et d'acide dans des sites miniers abandonnés se poursuit pendant des décennies ou des siècles, voire plus, après l'arrêt des activités d'extraction. La période de rejet dépend de chaque site minier. À l'échelle mondiale, on possède des renseignements sur la durée de rejet de métaux à des concentrations inacceptables dans le cas de quelques mines; l'information équivalente, dans le cas des sites miniers canadiens, est toutefois limitée.

Pourquoi l'INRE a-t-il effectué cette étude?

Au Manitoba, les rejets de sites miniers abandonnés ont une teneur élevée en métaux. Les sites en question constituent certains des plus anciens endroits où des résidus miniers ont été produits. Les résidus sont des déchets composés de particules très fines. L'exposition de ces déchets à l'oxygène de l'air entraîne l'oxydation de certains composés et le rejet de métaux. L'INRE a choisi d'étudier d'anciens sites miniers situés au Manitoba afin d'obtenir un aperçu de l'état futur des sites plus récents dans les autres régions du Canada.

Quels sont les résultats?

Le processus continu d'oxydation, pendant soixante-dix ans, se traduit par des eaux interstitielles de résidus ayant une teneur extrêmement élevée en métaux et en acide. Les concentrations observées sont beaucoup plus importantes que les valeurs correspondantes des sites miniers plus récents et elles peuvent offrir un aperçu de l'état de ces sites au fil des ans. Les eaux interstitielles s'écoulent des résidus dans un lac adjacent, ce qui entraîne la formation de nappes denses d'eau à très forte teneur en métaux au fond du lac. Des quantités importantes de métaux sont évacuées du lac dans une importante pêcherie locale.

Comment ces résultats seront-ils utilisés?

Les résultats serviront à élaborer un système de mesures correctives propres au site.

Quels étaient nos principaux partenaires dans cette étude?

Direction des mines du Manitoba; Conservation Manitoba; Université de Waterloo; Université de la Colombie-Britannique.

Fate and Transport of Metals from an Abandoned Tailings Impoundment after 70 Years of Sulfide Oxidation

M.C. Moncur[1], C.J. Ptacek[1,2], D.W. Blowes[1], and J.L. Jambor[1,3]

[1]*Department of Earth Sciences, University of Waterloo, Waterloo, ON*
[2]*National Water Research Institute, Environment Canada, Burlington, ON*
[3]*Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC*

Hydrogeological and geochemical studies of an abandoned high-sulfide tailings impoundment at Sherridon, Manitoba, were conducted during the summers of 2000 and 2001. The Sherridon tailings have undergone oxidation for more than 70 years. Mineralogical analysis indicates that the unoxidized tailings contain nearly equal proportions of pyrite and pyrrhotite that together make up to 60 wt.% of the tailings. Sulfides are extensively depleted in the upper few centimeters of the tailings. Sulfide oxidation has led to very high concentrations of dissolved iron and sulfate, elevated concentrations of trace metals, and the generation of low-pH conditions. Extensive accumulations of secondary melanterite, rozenite, jarosite, goethite, and gypsum have formed a massive continuous hardpan approximately 1 m below the tailings surface. The highest concentrations of dissolved metals are observed directly above and within the massive hardpan layer. During rainfall or other precipitation events, surface seeps along the flanks of the tailings develop and discharge pore water that has a geochemical composition resembling that of the water directly above the hardpan. These results suggest that shallow lateral flow of water due to a transient perched water table is resulting in higher contaminant loadings than are predicted by assuming that discharge is derived only from the much deeper primary water table. Groundwater and surface water from the tailings flow directly into a small lake adjacent to the impoundment. Samples from the water column of the lake show an abrupt increase in the metal concentrations at a 2-m depth, suggesting that higher density metal-laden water is accumulating at depth. Although the tailings have oxidized for >70 years, the presence of a significant amount of residual sulfide minerals suggests that metals and acid will be released for decades to centuries.

Introduction

The former Sherritt Gordon Cu-Zn mine is located in Sherridon, Manitoba (Figure 1). Mining began in 1928 and ended in 1951 when ore reserves were depleted. Copper and minor amounts of Au and Ag were initially recovered until 1942, and then a Zn concentrate was also produced. Over the mine life, approximately 7.4 million tonnes of high-sulfide tailings were discharged, covering an area of 50.6 ha (Acres International Ltd, 1986). The bulk of the tailings was deposited in two separate impoundments; Camp Tailings and Woods Tailings (Figure 2). The Camp Tailings were deposited from 1931 to 1932 and have oxidized for more than 70 years. The Woods Tailings were deposited from 1937 to 1951 and have oxidized for the last 50 years. Groundwater and surface water derived from both tailings impoundments flow directly into Camp Lake, which has been seriously impacted by acid and metal loading.
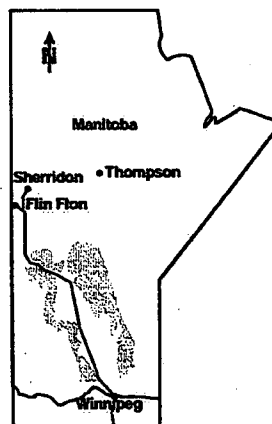

Figure 1. Location of Sherridon, Manitoba

The objective of this study is to quantify the extent of sulfide oxidation and to determine acid neutralization reactions within the unsaturated zone of the tailings after 70 years of weathering. A second objective is to evaluate the impact of tailings pore-water discharging to Camp Lake. A detailed field investigation was conducted during the summers of 2000 and 2001 to characterize the tailings solids, pore waters, and the surrounding surface waters.
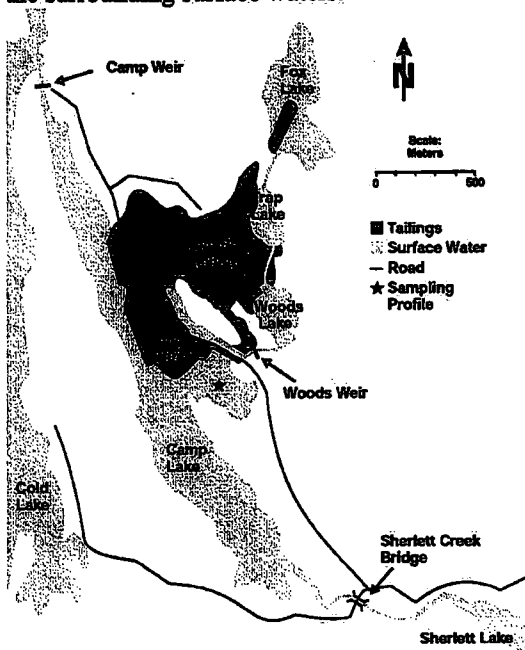

Figure 2. Site map showing location of the Camp and Woods tailings impoundments.

Materials and methods
Piezometer Network

The Sherridon tailings impoundments were instrumented with 11 piezometer nests (Figure 3). Five nests were installed across the Camp Tailings and six nests across the Woods Tailings. Each piezometer nest consists of two to six drive-point piezometers and/or bundle piezometers. Twelve single point piezometers were installed around the perimeter of the Camp Tailings to define the water table and pore-water geochemistry. Drive-point piezometers were installed in the tailings by direct push methods using a gas-powered vibrating hammer. Bundle piezometers were installed by pushing to depth a hollow drill-rod

casing with a knock-out tip on the bottom. The bundles were inserted into the drill rod, the drill rod was pushed to the desired depth, and removal of the drill rod allowed the tailings to collapse around the bundles. Rising-head bail tests were performed on all piezometers to estimate the hydraulic conductivity of the tailings.
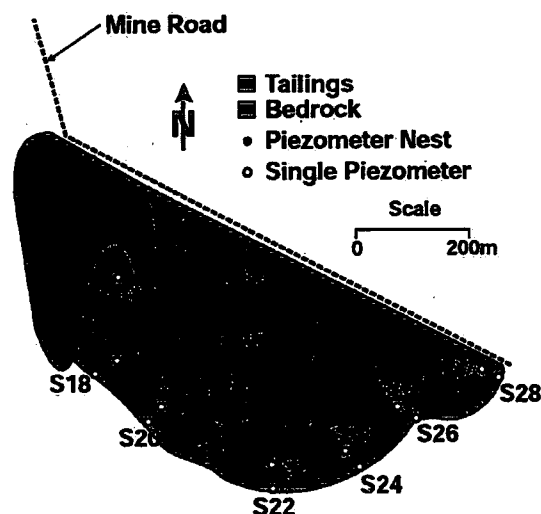

Figure 3. Piezometer nest and single-drive-point instrumentation in the Camp Tailings

Tailings Pore Gas

Samples of tailings pore gas were collected with drive-point sampling tubes and were analysed for O_2 and CO_2 in the field by using a portable meter, Nova model L8D50. Pore gas was measured at 10-cm increments from the surface of the tailings to a depth of gas depletion.

Tailings Solids

Continuous cores of the tailings were collected at all piezometer-nest locations from the tailings surface to the refusal depth. Cores were collected in thin-walled irrigation tubes, 5.1 cm (2 ins) or 7.6 cm (3 ins) in diameter, with a core catcher attached on the bottom. When hardpan was encountered, a backhoe was used to excavate a pit through the hardpan until unconsolidated tailings were reached. At the bottom of the excavated pit, tailings samples were collected using a piston-core barrel method described by Starr and Ingleton (1992). Samples of hardpan were collected from the walls of the excavated pit by means of a horizontal coring method using 2-

inch or 3-inch aluminium tubing. All cores except S3 were cut into 20-cm to 30-cm sections, then immediately frozen, whereas the S3 cores were sampled immediately to determine their pore-water compositions. From each location, one core was collected for pore-water analysis and the second core was used for analysis of the solids. Mineralogy of the tailings was determined using transmitted- and reflected-light microscopy, scanning electron microscopy, bulk-sample X-ray diffractometry, and supplementary electron-microprobe analyses and Debye–Scherrer X-ray diffraction patterns. Total extractable carbonate was measured using the method of Barker and Chatten (1982), and total sulfur was determined by the LECO induction furnace.

Tailings Pore-Water Sampling

Pore water from the vadose zone was sampled by squeezing cores of the tailings. Cores from S3 were squeezed in the field, and all others were shipped frozen to the University of Waterloo. At the University of Waterloo, the core sections were thawed prior to squeezing. A method similar to that of Patterson *et al* (1978), as later modified by Smyth (1981), was used to extract pore water. The pore-water samples were collected in 60-mL syringes and were passed through cellulose-nitrate filters. Pore-water Eh and pH were determined at least three times during the collection of each unfiltered sample to obtain representative results. The Eh was measured using an Orion platinum redox electrode (model 96-78BN), calibrated in Zobell's solution (Nordstrom, 1977) and Light's solution (Light, 1972). The pH was measured using an Orion Ross combination electrode (model 815600), calibrated with standard buffer solutions at pH 7, 4, and 1. Measurements of alkalinity were made with a Hach digital titrator using bromcresol green/methyl red indicator on filtered samples with 0.16 N H_2SO_4. One sample was acidified with 12 N analytical grade HCl to a pH of less than one for cation analysis. The second sample was unacidified and was used for anion analysis. All samples were refrigerated until analysis.

Groundwater Sampling

Pore water from the saturated zone was collected from all piezometers by using a peristaltic pump and polyethylene tubing. All piezometers were bailed dry and allowed to recover prior to sampling. Measurements of Eh and pH were made in a sealed flow-through cell, maintained at groundwater temperature in a water-ice bath (~8 to10°C). Calibration of the Eh and pH probes was checked after each sampling point. Temperature and alkalinity were measured at each location. Samples were filtered with cellulose-nitrate filters and split into two samples for anion and cation analysis. All samples were refrigerated until analysis, which was done with the same methods as for samples collected from the vadose zone.

Surface-Water Sampling

Samples of surface water were collected at Camp Lake, Camp Weir, Woods Weir, Sherlett Creek Bridge, and two groundwater discharge zones. Camp Weir, Woods Weir, and Sherlett Creek Bridge were sampled bi-weekly between July 15, 2001 and October 5, 2001. Depth profiles at 1-m intervals from surface were performed at 11 stations in Camp Lake. At each depth profile in Camp Lake, dissolved oxygen and temperature were measured using a Hydrolab model H_2O, and samples were collected with a 3-L Van Dorin Bottle Sampler. The pH and Eh were measured through a sealed flow-through cell maintained at lake-water temperature in a water bath. Alkalinity was also measured at each location. Samples were passed through cellulose-nitrate filters and were split into two samples for anion and cation analysis. All samples were refrigerated until analysis.

The field and laboratory samples were analyzed for cations and anions by the National Laboratory for Environmental Testing, Burlington, Ontario. The cation samples were analyzed for Al, Ba, Be, B, Cd, Ca, Cr, Co, Cu, Fe, Pb, Mg, Mn, Mo, Ni, K, Si, Na, Sr, V, Zn, and As by inductive coupled plasma optical emission spectrometry (ICP–OES). The anions Cl and SO_4, were determined by an automatic colorimetric procedure. Quality control and accuracy evaluation included analyzing several standards spanning a range of concentrations, analysis of field replicates and splits, and addition of standards to unknown samples to assess for matrix effects. Groundwater chemistry was evaluated using the equilibrium mass transfer model MINTEQA2 (Allison, 1990). The MINTEQA2

data base was modified to make it consistent with that of WATEQ4F (Ball, 1991). MINTEQA2 calculates the saturation indices for discrete mineral phases and allows redox potentials (Eh) to be entered either as measured Eh or calculated from a measured redox couple. In acid mine waters, high activities of both $Fe(III)$ and $Fe(II)$ provide a dominant and reversible couple that balance Eh measurements (Nordstrom, 1979). Pore water from the Sherridon tailings contains high concentrations of dissolved $Fe(III)$ and $Fe(II)$, resulting in measured Eh values being suitable for use in the geochemical modelling.

Results and Discussion
Hardpans

The Sherridon tailings have two distinct types of cemented layers or hardpans. A massive (>1 m thick) hardpan is present throughout the impoundment at a depth of 1–2 m. The hardpan is continuous throughout the impoundment, but pinches out at the edges adjacent to water bodies and zones of groundwater discharge. The hardpan at piezometer nest S3 is 50 cm below the zone of active oxidation and is cemented by both secondary $Fe(II)$ and $Fe(III)$ minerals, mainly melanterite, rozenite, jarosite, and goethite. Gypsum is also present as a cement-forming secondary mineral within the hardpan. Blowes *et al.* (1991) encountered a similar hardpan layer at the Heath Steele mine in New Brunswick, Canada. The high sulfide content in the tailings consumes atmospheric O_2 near the tailings surface, reducing $Fe(III)$ to $Fe(II)$ deeper in the tailings. This reaction results in lower concentrations of $Fe(III)$, whereas concentrations of $Fe(II)$ and sulfate are high enough to attain saturation with respect to ferrous sulfate minerals below the zone of oxidation (Blowes *et al.*, 1991).

Above the continuous hardpan, in the zone of active oxidation, are thin (1 to 10 cm), discontinuous cemented layers composed of secondary goethite, jarosite and gypsum. Similar $Fe(III)$-bearing hardpans were observed at the Waite Amulet tailings area in Quebec (Blowes *et al.*, 1990), the Copper Cliff tailings impoundment near Sudbury, Ontario (Coggans *et al.*, 1999), and the Nickel Rim tailings site near Sudbury (Johnson *et al.*, 2000). At the Sherridon tailings, it is possible that the massive hardpan migrates downward in advance of the oxidation front, and

the thin discontinuous hardpans are oxidized remnants of the original massive hardpan.

High moisture contents were observed above the continuous hardpan at S3. The moisture content increases from the tailings surface to the top of the massive hardpan, then sharply decreases within the hardpan layer (Figure 4). This increase in moisture content above the continuous hardpan suggests that the formation of this layer affects water flow through the tailings. The permanent water table is 4 m below the hardpan near S3. The flow of vadose-zone-derived groundwater can be due either to a transient rise in the water table during storm events (Blowes *et al.*, 1988; Al *et al.*, 1995) or to perched water-table conditions. It is hypothesized that the principal transport of metals to the surface-water flow system is the result of groundwater flow along the transient perched water table. This flow is constrained by the hydraulic characteristics of the hardpan layer.

Sulfide Oxidation

The Sherridon tailings consist of up to 60 wt% sulfide minerals, principally pyrrhotite and pyrite. The ratio of the pyrite:pyrrhotite in the orebody was estimated by Farley (1949) to be 2:1, however, microscopy examinations of the tailings indicate that the ratio of pyrrhotite:pyrite is 1:1 to 2:1, with pyrrhotite equalling or exceeding pyrite in all samples. Other sulfide minerals present in the tailings are sphalerite, chalcopyrite, and trace amounts of arsenopyrite and marcasite. Grains of cubanite and galena in the ore were observed by Farley (1949), but these minerals were not detected in the tailings.

Pore-gas concentrations measured at S3 show an abrupt depletion in atmospheric oxygen (O_2) at a depth of 40 to 50 cm (Figure 4). An abrupt increase in sulfide minerals coincides closely with the O_2 depletion. The depletion in pore-gas O_2 is a direct result of O_2 consumed by the oxidation of pyrrhotite, pyrite, and other sulfide minerals in the tailings.

Core extracted from piezometer nest S3 is visibly oxidized to a depth of 90 cm, at which the massive hardpan layer begins. Extensive oxidation has occurred in the upper 30 cm of the tailings, completely obliterating the sulfide minerals. At a depth of 40 cm, pyrite and chalcopyrite have not been oxidized, but

sphalerite and pyrrhotite are absent. The first appearance of sphalerite occurs at a depth of 60 cm. Pyrrhotite first appears at 90 cm as remnant cores within pseudomorphs of marcasite. At a depth of 115 cm, well developed cores of pyrrhotite are present and marcasite is restricted to narrow alteration rims. Carbonate minerals in the unsaturated zone make up less than 0.05 wt% of the Camp Tailings. Mineralogical analysis indicates that carbonate minerals are absent in the unsaturated zone of the S3 profile, except at a depth of 91 cm and 114 cm, where a few grains of siderite were observed.
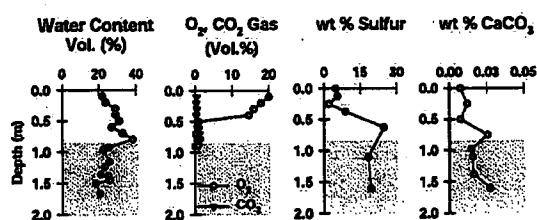

Figure 4. Depth profile of moisture content, concentrations of O_2 and CO_2 gas, and weight percent of sulfur and carbonate mineral measured at S3. Shaded area represents hardpan.

Acid Neutralization

The oxidation of sulfide minerals results in the release of acid into the tailings pore water. Gangue minerals incorporated in the tailings can neutralize acid-producing reactions. Examples of gangue that can contribute to acid-neutralizing reactions include calcite, dolomite, and aluminosilicate minerals. Their dissolution typically leads to a distinct sequence of pH-buffering plateaus (Blowes and Ptacek, 1994; Jurjovec *et al.*, 2002). Gangue minerals contributing to acid-neutralization reactions in the Sherridon tailings are predominantly aluminosilicates, which include biotite, chlorite, and possibly smectite. The extremely low pH of the pore water in the upper vadose zone of the Sherridon tailings has depleted nearly all biotite and chlorite to the top of the massive hardpan layer. There is also evidence of secondary replacement of other aluminosilicates above the hardpan, namely, plagioclase, cordierite, and amphibole.

The first appearance of biotite occurs at 72 cm, which coincides with the first appearance of secondary sulfides (marcasite). Chlorite and

smectite first appear at a 90 cm depth. The depletion of aluminosilicate minerals in the upper meter of the tailings, and the presence of a significant amount of residual sulfide minerals in this zone, suggest that the tailings will remain acid-generating.

Vadose-Zone Pore Water

Sulfide oxidation at the Sherridon tailings has resulted in the generation of low-pH tailings pore water that contains high concentrations of metals and sulfate. The oxidation of pyrrhotite and pyrite results in the release of Fe, SO_4 and acid. The pH of the tailings pore water ranges from 0.7 to 2 near the surface of the tailings, increases sharply where the continuous hardpan is first encountered, and gradually continues to increase with depth. At the majority of locations sampled, high concentrations of Fe, SO_4, and most dissolved metals coincide with low pH conditions (<1) at the top of the hardpan and increase with depth through the hardpan to just above the water table. Elevated concentrations of Fe (129,000 mg/L), SO_4 (280,000 mg/L), Zn (54,900 mg/L), Al (5,710 mg/L), Cd (97 mg/L), Co (105 mg/L), Cu (1,620 mg/L), Cr (3.1 mg/L), Mn (261 mg/L), Ni (15.3 mg/L), Pb (5.2 mg/L), and As (41 mg/L) were observed in the vadose zone of the Camp Tailings impoundment (Figure 5). Rarely at any location was measurable alkalinity detected in the unsaturated zone.

Groundwater

Near the water table, the concentrations of most metals and sulfate show a sharp decline in concentrations. These results suggest that the concentration of metals and sulfate decrease near the water table because of dilution caused by horizontal and vertical groundwater flow in the capillary fringe and saturated zone. Although dissolved metals and sulfate concentrations are lower below the water table than concentrations observed in the vadose zone, the concentrations are still elevated throughout the Camp Tailings, with Fe and SO_4 values up to 60,600 mg/L and 91,600 mg/L respectively (Figure 6). Across the Camp Tailings, from piezometer nest S4 to S1, high concentrations of Fe, SO_4, Zn, Al, Cu, Cr, Co, Cd, Pb, Ni, and As were detected in nearly all piezometers. Alkalinity in the groundwater ranges between 0 and 127 mg/L (as $CaCO_3$), with the highest values observed deep in the

impoundment. The concentrations of Fe and SO_4 at the Camp Tailings are among the highest values reported for mine-waste accumulations in Canada.
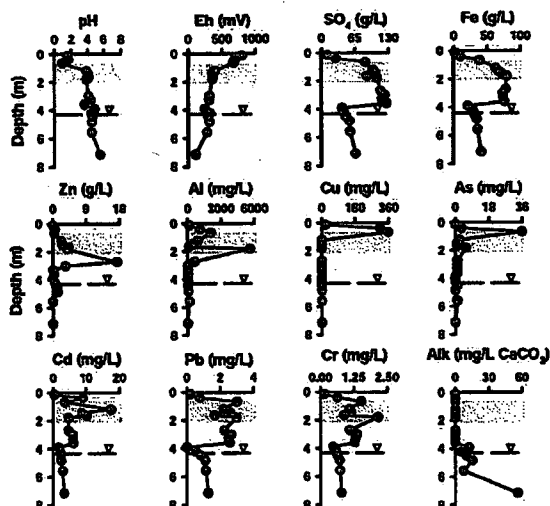

Figure 5. Water chemistry profiles for piezometer nest S3. The water table is represented by dashed line. Shaded area represents the extent of hardpan. Note: SO_4, Fe, and Zn are in g/L.

Shallow single-drive-point piezometers (1 m depth) installed around the perimeter of the Camp Tailings indicate that the pH of the pore water above the hardpan varies from 3.6 to 4.2. The highest concentration of metals and sulfate occur in the piezometers farthest from the shore of Camp Lake: S17, S21, S23, S25, and S27. The higher concentration of dissolved metals is related to a lower water table and to extensive sulfide oxidation within the upper portions of the tailings. In areas where piezometers are adjacent to Camp Lake, the water table is near or at the surface of the tailings. The higher water table results in slightly lower concentrations of metals and sulfate because of dilution and less extensive sulfide oxidation. Results from the single drive-point piezometers adjacent to Camp Lake indicate that high concentrations of metals, sulfate, and acid are discharging directly into the lake.

During atmospheric precipitation, surface seeps form along the flanks of the tailings impoundment, discharging pore water with a geochemical composition that is similar to the composition of water directly above and within the hardpan. Seepage water contains high concentrations of Fe (67,800 mg/L), SO_4 (151,000

mg/L), Zn (164 mg/L), Al (1130 mg/L), Cd (3.9 mg/L), Mn (103 mg/L), Pb (1.7 mg/L), and As (1.8 mg/L). Along the fringes of the seepage zones, there is an accumulation of the ferrous iron mineral melanterite. The formation of melanterite indicates that most of the iron in the pore water is present as Fe(II). The low pH of the seepage water may be preventing the water from oxidizing and precipitating as Fe(III) minerals. There is no visual evidence of Fe(III) precipitates along the flowpath of the seepage water until it discharges into surface water bodies, at which point massive accumulations of Fe(III) minerals were observed. These results suggest that shallow lateral flow of water due to a transient perched water table is resulting in the discharge of high concentrations of metals, sulfate, and acid to the tailings surface and adjacent water bodies.

Equilibrium calculations conducted using MINTEQA2 indicate that pore water and groundwater within the Camp Tailings are strongly undersaturated with respect to carbonate minerals. Calculations also suggest that the tailings pore water reaches saturation with respect to melanterite, rozenite, jarosite, goethite, and gypsum within the hardpan at a pH of 4. These results suggest that gypsum and ferrous and ferric iron minerals are important controls on the concentrations of dissolved constituents within the Camp Tailings.

Surface Water

Approximately 95% of the water that enters Camp Lake is derived from Sherlett Creek, which flows into the southeastern end of the Lake. Water sampling indicates that the pH, sulfate, and dissolved metals remained constant over the study period. The water in Sherlett Creek has an average pH of 7.4, and most metals except Cu, Zn, and Al are below their detection limits. The increase in Cu, Zn, and Al concentrations is likely related to the use of waste rock and tailings from the Sherritt Gordon mine for construction material adjacent to Sherlett Creek. Upstream from the sampling station, roads near Sherlett Creek are constructed from waste rock that contains visible sulfide minerals. Along the bank of Sherlett Creek are small waste-rock and tailings piles. Some of the waste rock and all of the tailings along Sherlett Creek show extensive sulfide oxidation, the effect

of which is a release of metals and acid into Sherlett Creek.
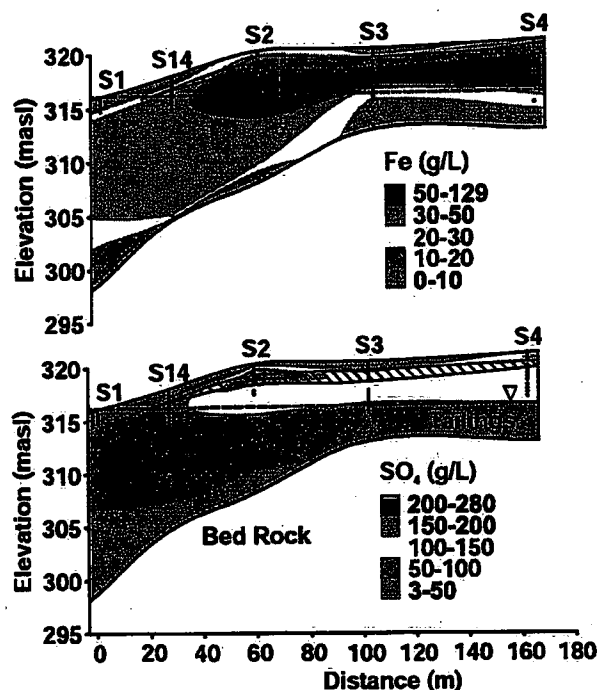

Figure 6. Iron and sulfate concentrations across the Camp Tailings. Black dots represent sampling points. Dashed line represents the water table. Cross-hatched area indicates extent of hardpan.

A second smaller tributary flowing into Camp Lake through Woods Weir accounts for approximately 2% of the input to the lake (Figure 2). The headwaters of this watershed are at Fox Lake, which has a pH of 7.97, an alkalinity of 62 mg/L, and in which all metals are below their detection limits and those for drinking-water standards. Water flows from Fox Lake into Trap Lake, where mine drainage from the Woods Tailings has seriously impacted the surface water. The pH drops abruptly to 2.5 at Trap Lake, then drops to 2.3 in Woods Lake. Both Trap Lake and Woods Lake contain elevated concentrations of metals and sulfate. Water flows from Woods Lake into Camp Lake through the Woods Weir. Water flowing through Woods Weir has a deep red-wine color and an average pH of 2.17. Metals in the water are extremely elevated, with Fe up to 1738 mg/L, SO_4 up to 5350 mg/L, and with other metals well above the maximum concentrations for drinking water and the protection of freshwater aquatic life (Environment Canada,

1998; Federal-Provincial Subcommittee on Drinking Water, 1996). Although flow through Woods Weir makes up only a few percent of the total input into Camp Lake, the stream has a severe impact in terms of metal loading. Although large, this input is, however, less than that derived from groundwater discharge from the Camp Tailings.

Metal and sulfate concentrations in Camp Lake are elevated, particularly in an isolated bay (Camp Lake Bay). There, at a depth of approximately 2 m, a sharp thermocline coincides with an increase in dissolved ions (Figure 7). Elevated concentrations of Fe (8850 mg/L), SO_4 (19,300 mg/L), Zn (31 mg/L), Al (101 mg/L), Cd (0.72 mg/L), Co (0.08 mg/L), Cu (4.6 mg/L), Cr (0.15 mg/L), Mn (20 mg/L), Ni (0.016 mg/L), Pb (0.34 mg/L), and As (0.3 mg/L) were observed in the water column. Samples of lake water have compositions similar to those collected in shallow wells from the tailings. These high concentrations may indicate that higher density, metal- laden pore water from the tailings have accumulated in Camp Lake for a sufficiently prolonged period to have caused severe degradation of the quality of the surface water.

Water empties from Camp Lake through the Camp Weir and discharges directly into Cold Lake. The average pH of the water flowing over the weir is 3.3, with elevated concentrations of Fe (11 mg/L), SO_4 (112 mg/L), Al (1.35 mg/L), Zn (0.63 mg/L), Pb (0.15 mg/L), and Cu (0.12 mg/L). The pH and concentrations of Fe, SO_4, Al, Zn, Cu, and Pb are all well above the maximum concentrations for the protection of freshwater aquatic life.

Conclusions

Pore waters in the Sherridon tailings have very high concentrations of dissolved metals, sulfate, and acid as a result of seven decades of sulfide oxidation reactions. Low pH (<1) pore water in the vadose zone has depleted nearly all biotite and chlorite, and possibly smectite, above the hardpan, but less than 50 % of the sulfide-mineral content has been consumed. This abundance of sulfide minerals and depletion of neutralizing minerals indicate that the Sherridon tailings will continue to release high concentrations of acid, sulfate, and metals for many years to come.
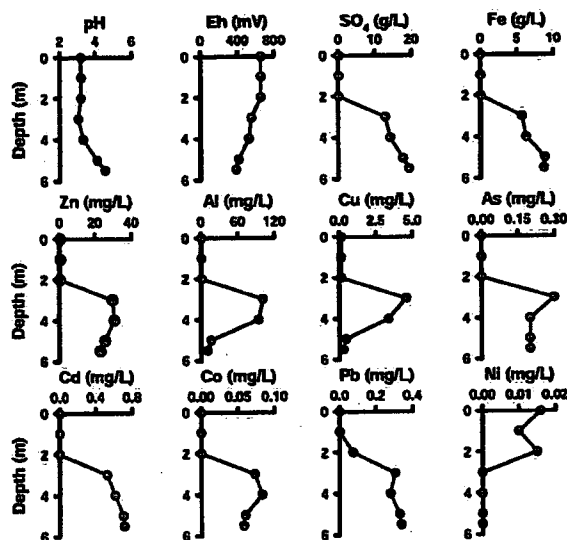
Figure 7. Water chemistry profiles for Camp Lake Bay. Note: SO4, and Fe are in g/L.

During atmospheric precipitation events, surface seeps along the flanks of the tailings impoundment develop and discharge pore water with a geochemical composition that is similar to that of water directly above and within the hardpan. The shallow lateral flow of water due to a transient perched water table above the hardpan may be reducing recharge to the underlying water table. The discharge of surface and groundwater from the Sherridon tailings has degraded the water quality of Camp Lake. Localized zones within Camp Lake show high concentrations of metals and sulfate with increasing depth.

Acknowledgements

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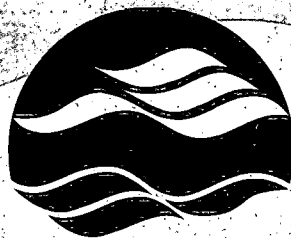
National Water Research Institute
Environment Canada
Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

**NATIONAL WATER
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Institut national de recherche sur les eaux
Environnement Canada
Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington, Ontario
L7R 4A6 Canada

Centre national de recherche en hydrologie
11, boul. Innovation
Saskatoon, Saskatchewan
S7N 3H5 Canada

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