

Evaluation of Trace Element Mobility in a Sandy Aquifer of the Athabasca Oil Sands, Alberta

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Extended Abstract

1. Introduction

The Athabasca oil sands deposit, located in Northeastern Alberta, is the largest oil reservoir in the world. Alberta's oil sands industry extracts bitumen from these deposits and produces crude oil by additional processing. The produced tailings, a mixture of sand, silt, clay, water, residual bitumen, other hydrocarbons, and salts, are contained in impoundments that are generally constructed over low permeability glacial till and/or shale bedrock. However, in some cases, the glacial tills contain paleochannels that may provide migration pathways for process-affected (PA) water away from the tailings deposits. For example, Suncor's South Tailings Pond (STP) is partially situated atop the Wood Creek Sand Channel (WCSC), a highly permeable Pleistocene glacial outwash channel (Holden et al., 2009; Tompkins, 2009). The location of the STP implies that during reclamation, removal/remediation of PA water and treatment of mature fine tailings using the wet landscape method may only partially restore this area as it does not address the effect on the underlying groundwater system (Tompkins, 2009). Therefore, a detailed understanding of trace metal mobility as a potential consequence of the PA water infiltration into the WCSC is essential in developing sustainable strategies to reclaim the STP.

As part of a larger project, this study aims to investigate the impact of PA water ingress on metal speciation, redox state, and trace metal mobility. To assess metal release under field conditions, a series of PA water injections has been conducted in the WCSC aquifer located adjacent to an existing aquifer test facility. Groundwater data collected prior to PA water injection suggest that the natural aquifer conditions are mildly anaerobic and that trace metal concentrations are relatively low. Following PA water injection, the levels of dissolved Fe, Mn, Ba, Co, Sr, and Zn increased above background levels. It is likely that ion exchange or surface complexation reactions and microbially-mediated reductive dissolution of Fe and Mn oxides (including hydroxides, oxyhydroxides and hydrous oxides; hereafter referred to as oxides) released Fe(II), Mn(II) along with associated Ba, Co, Sr, and Zn into solution (Tompkins, 2009). However, solid phase speciation data is needed to elucidate the biogeochemical processes controlling the observed increase in metal concentrations. To evaluate the solid phase distribution of trace elements, pristine core samples collected from within the WCSC were assessed by a previously established sequential extraction method. Here, the distribution and possible mechanisms governing the fate of inorganic trace contaminants of concern in the WCSC are addressed.

2. Previous Research Work

Measurements of a number of redox sensitive parameters (e.g., dissolved oxygen, N species, Mn(II), Fe(II), SO₄) under baseline conditions indicate that the WCSC groundwaters are manganogenic and ferrogenic (Tompkins, 2009). Following PA injection, the groundwater data suggests that elevated levels of dissolved organic carbon (DOC) from the injectate may have initiated dissimilatory reduction of Mn(IV) and Fe(III) oxides, and the subsequent release of Fe(II), Mn(II), along with Ba, Co, Sr and Zn into solution (Figure 1).

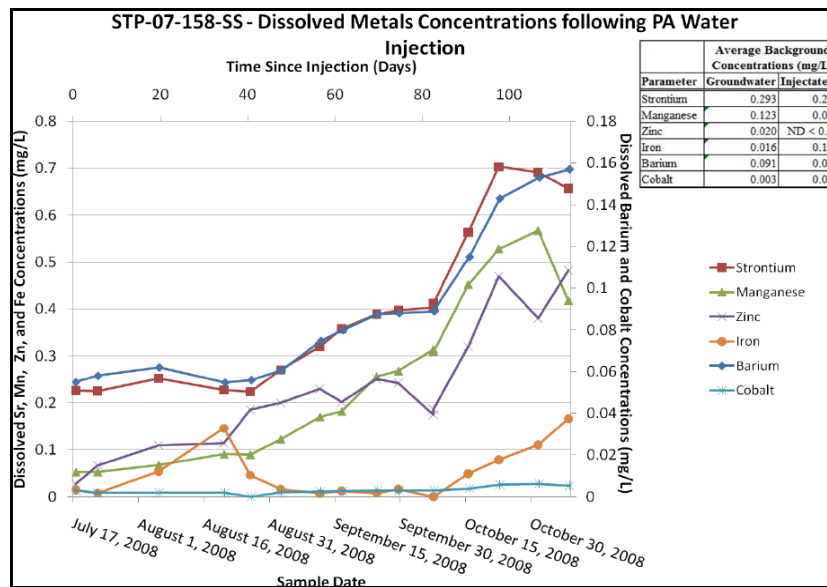


Figure 1. Dissolved metal concentrations following PA water injection at well STP-07-158-SS. Select trace elements that exhibit rising concentration trends not attributable to elevated injectate levels or a return to background conditions are shown (Tompkins, 2009).

3. Solid Phase Chemistry of WCSC Sediments

A sequential extraction method based on Herbert (1997) was employed to assess the relative significance of “operationally defined” fractions of elements that are present in the undisturbed WCSC sediments. These fractions characterize metals as: (1) exchangeable, (2) acid-soluble (bound to amorphous and poorly crystallized Fe and Mn oxides), (3) reducible (bound to well crystallized Fe and Mn oxides), (4) bound to organic matter, and (5) those contained in residual minerals. All supernatants were analyzed for Fe, Mn, Ag, Al, As, Ba, Cd, Co, Cr, Cu, Ni, Pb, Sb, Sr, V, and Zn using inductively coupled plasma optical emission spectroscopy (ICP-OES).

The exchangeable fraction (F1), commonly regarded as the most mobile form of soil elements, includes weakly-sorbed species, chiefly those retained on mineral surface exchange sites by relatively weak electrostatic attraction (Hall et al., 1996). The extraction results demonstrate that the F1 fraction is small relative to the total elemental concentrations (Figure 2). Ingressing high-ionic-strength PA water is expected to displace a portion of the sorbed trace elements into solution. Mass balance calculations suggest that the observed concentration changes in the pore water (Figure 1) could be significantly influenced by releases from this fraction.

Of key interest to the present study are the trace elements associated with the acid-soluble (F2) and reducible (F3) fractions because the groundwater injection experiment data suggested that trace metal mobilization following PA water injections is likely affected by the microbially-mediated reduction of metal oxides. The fractionation data confirm that trace elements associated with F2 and F3 account for a substantial portion of the total elemental content in these sediments (Figure 2). In particular, F2 extractable Fe was found at concentrations of > 50 mg kg⁻¹ for each depth interval. In addition, > 2 mg kg⁻¹ of F2 extractable Mn was found in deeper core sections. Moreover, the extraction data indicates that Sr and Zn, two of the trace elements whose dissolved concentrations increased above background levels following the PA water injections, were also associated with F2 at concentrations of > 1 mg kg⁻¹.

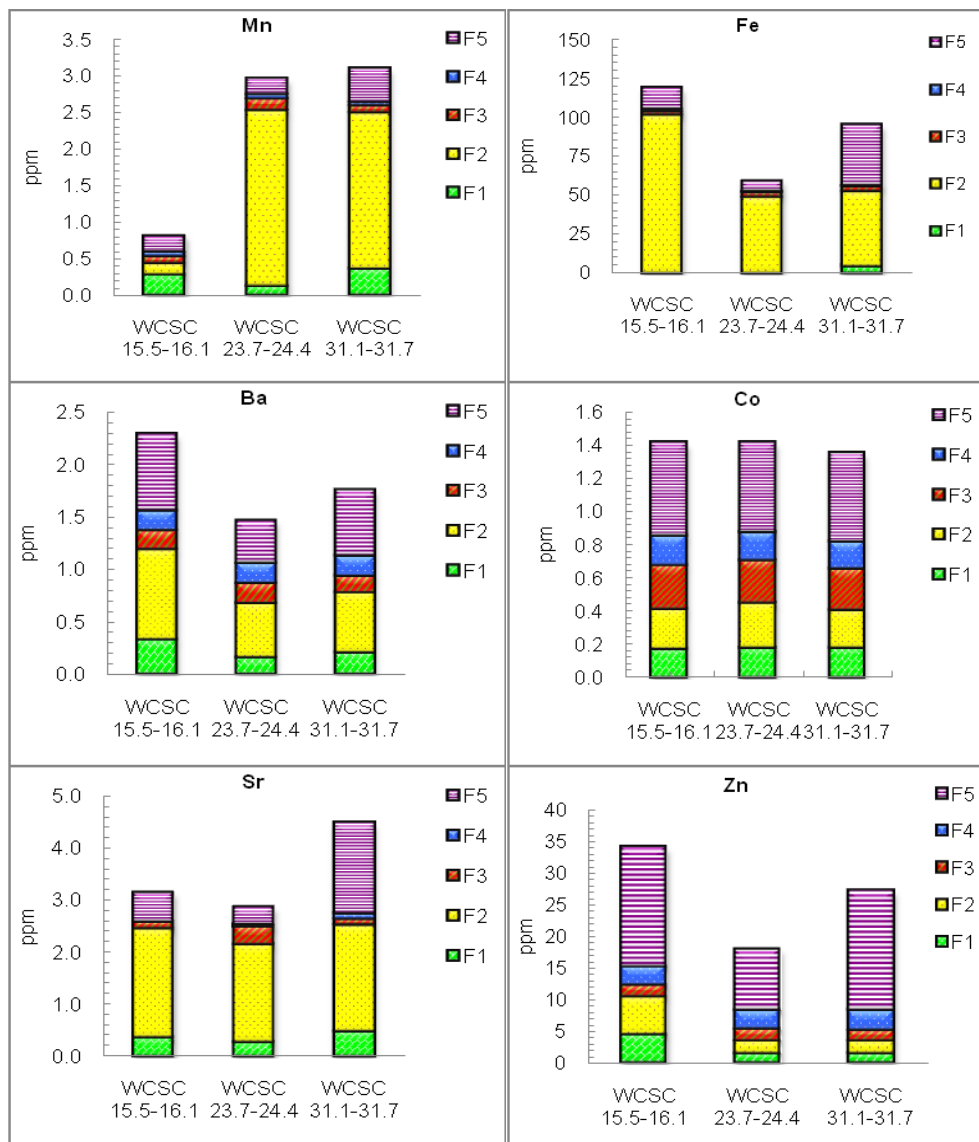


Figure 2. “Operationally defined” fractions of select trace metals in WCSC sediment samples.

The F2 and F3 fractions are sensitive to varying pH values; amorphous and crystalline Fe and Mn oxides, as well as metals associated with these phases can be released by reducing the pH. However in the near-neutral waters ($6.6 < \text{pH} < 7.6$) of WCSC, Fe is likely to exist as insoluble Fe(II) or Fe(III) minerals (Cornell and Schwertmann, 2003), and increasingly reducing conditions are needed for mineral dissolution. An alternate explanation is therefore that the introduction of PA water into the WCSC groundwaters, with elevated levels of DOC may have altered the in-situ redox conditions and facilitated the microbial reduction of Fe(III) and Mn(IV) oxides and subsequent mobilization of the associated trace elements. We can infer from our aqueous and solid phase data that Fe and Mn reducers (e.g., members of *Geobacteraceae*; Lovley et al., 1990) likely play an important role in the cycling of trace elements in these aquifers.

The trace elements bound to the organic phase (F4) represent a minor fraction of the total extractable elements. In F4, the elements are associated with stable high molecular weight humic substances that release small amount of trace elements in a sluggish manner, and are considered immobile and not bioavailable (Garcia-Miragaya and Sosa, 1994).

The sequential extraction results further suggest that a major portion of the elements examined is in the residual mineral fractions (F5) that are relatively stable compared to redox-sensitive metal oxides. The residual phase consists of primary and secondary minerals that contain trace elements in the crystalline lattice, and the associated elements can only mobilize as a result of weathering. Thus, F4 and F5 are unlikely sources of trace metals to the studied groundwaters.

4. Concluding Remarks

The research described herein identified that the observed mobilization of trace elements induced by the injection of PA water can be explained by exchange reactions and/or dissimilatory reduction of amorphous and poorly crystalline Fe and Mn oxides. To more completely address this issue, a detailed understanding of the biogeochemical mechanisms, and the effect of such processes on cycling of trace elements in groundwater systems of the Athabasca oil sands region, is required. To this end, ongoing experiments will characterize the mineralogical compositions of the core samples by a combination of X-ray Diffraction and Scanning Electron Microscopy techniques. Future work will characterize the solid phase partitioning not of pristine samples but of sediments impacted by PA water, and will be supported by collaborative research concerning the influence of in-situ microbial communities in these same samples.

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