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Characterization of physical mass transport through oil sands fluid fine tailings in an end pit lake: a multi-tracer study

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ABSTRACT

Soft tailings pose substantial challenges for mine reclamation due to their high void ratios and low shear strengths, particularly for conventional terrestrial reclamation practices. Oil sands mine operators have proposed the development of end pit lakes to contain the soft tailings, called fluid fine tailings (FFT), generated when bitumen is removed from oil sands ore. End pit lakes would be constructed within mined-out pits with FFT placed below the lake water. However, the feasibility of isolating the underlying FFT has yet to be fully evaluated. Chemical constituents of interest may move from the FFT into the lake water via two key processes: (1) advective-diffusive mass transport with upward pore water flow caused by settling of the FFT; and (2) mixing created by wind events or unstable density profiles through the lake water and upper portion of the FFT. In 2013 and 2014, temperature and stable isotopes of water profiles were measured through the FFT and lake water in the first end pit lake developed by Syncrude Canada Ltd. Numerical modelling was undertaken to simulate these profiles to identify the key mechanisms controlling conservative mass transport in the FFT. Shallow mixing of the upper 1.1 m of FFT with lake water was required to explain the observed temperature and isotopic profiles. Following mixing, the re-establishment of both the temperature and isotope profiles required an upward advective flux of approximately 1.5 m/year, consistent with average FFT settling rates measured at the study site. These findings provide important insight on the ability to sequester soft tailings in an end pit lake, and offer a foundation for future research on the development of end pit lakes as an oil sands reclamation strategy.

1. Introduction

Soft tailings are a fluid-like by-product of the milling or extraction processes associated with mining. Conventional terrestrial reclamation of this mine waste requires stabilization of the soft tailings to increase their bearing capacity and shear strength before a soil cover is placed over the tailings. One alternative approach developed for the disposal of this material is to place the soft tailings within depleted mine pits and cover them with a water cap. Oil sands operators plan to employ this strategy as a means of reducing their inventory of soft tailings produced by the extraction of bitumen from oil sands ore, referred to as fluid fine tailings (FFT). Oil sands operators have proposed the development of thirty 'end pit lakes', half of which will incorporate unprocessed FFT below the lake water (Prakash et al. 2011).

The development of end pit lakes would allow oil sands operators to decrease the volumes of FFT stored in tailings impoundments; however, the feasibility of isolating FFT from the overlying water and establishing a sustainable biological community in the lake have yet to be fully evaluated. The FFT pore water generally contains high concentrations of dissolved constituents, naphthenic acids, petroleum hydrocarbons, and unrecovered bitumen (Allen 2008; Dompierre et al. 2016;

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Kavanagh et al. 2011). These constituents may move from the FFT into the lake water via two key processes: (1) advective-diffusive mass transport with upward pore water flow caused by dewatering of the soft tailings; and (2) mixing created by wind events or unstable density profiles through the lake water and upper portion of the FFT. The long-term biogeochemical evolution of the FFT is being studied but is currently unknown; however, the mechanisms controlling the transport of heat and aqueous constituents will remain key foundational processes in the development of this understanding.

This study presents a preliminary assessment of the movement of the stable isotopes of water (deuterium, ^2H; oxygen-18, ^{18}O) from the FFT to the water cap of the first end pit lake developed in the Athabasca oil sands region. These isotopes serve as conservative tracers for potential chemical transport since they are components of the water molecule. The concentrations of these isotopes are generally represented in terms of differences in the isotopic ratios (i.e. $^2H/^1H$ or $^{18}O/^{16}O$) from known standards, according to the 'del' notation (δ). The isotopic composition of a water sample can be used to identify its source (Coplen et al. 2000). This method has been applied in many different fields, including: (1) hydrology, to measure evaporation and precipitation trends (Gammons et al. 2006; Gibson et al. 1996), and to determine the water balance of catchments and lakes (Gibson et al. 2005; Gibson and Edwards 2002); (2) hydrogeology, to track the movement of water through aquitards (Hendry and Wassenaar 2011), and assess groundwater recharge rates and residence times (Buttle 1998; McGuire et al. 2005; Taylor and Howard 1996); and (3) contaminant transport to determine advection and diffusion of conservative species (Barbour et al. 2012; McKay et al. 1993). Stable isotopes of water have more recently been employed in the oil sands to characterize the isotopic signatures of various natural and mine affected waters (Baer 2014), to trace the movement of process-affected waters (Gibson et al. 2011), and to evaluate recent recharge into overburden deposits (Huang et al. 2015). Therefore, stable isotopes of water are an appropriate tracer to assess mass transport through the FFT in Base Mine Lake.

Heat was also used as a tracer for evaluating the mechanisms controlling the movement of conservative aqueous constituents in the FFT. Heat has been employed to trace the movement of groundwater (Anderson 2005; Bredehoeft and Papadopulos 1965; Saar 2011; Stallman 1965), and can be used to evaluate interactions between surface and groundwater systems (Blasch et al. 2007; Constantz 2008; Stonestrom and Constantz 2003; Suzuki 1960). Heat transfer via convection is mainly driven by fluid flow; therefore, convective heat transfer can be used as a tracer for advective mass transport through the FFT. Convection may be either: (1) forced convection, in which the movement of heat is due to hydraulically driven water flow; or (2) free convection, in which fluid flow occurs as a result of temperature-derived density differences (Anderson 2005; Pop and Ingham 2001). In an end pit lake, forced convection would result from the upward movement of water associated with FFT densification. Free convection could occur within the FFT if substantial temperature-induced density differences form.

Heat transfer between the water cap and underlying FFT in an end pit lake may also occur as a result of conduction. Conduction is the transmission of heat from more energetic molecules to those with less energy (Rathore and Kapuno 2011). The lake temperature changes seasonally with air temperature, causing conduction to occur over the FFT-water interface. Conduction is generally more effective in moving heat than diffusion is in moving mass, so heat cannot be used as a direct tracer for diffusive mass transport. However, if convection is shown to be an important mechanism for heat transport through the FFT, then advection will be integral to mass transport.

Movement of the lake water itself may also play an important role in heat and mass transport through the FFT. Wind-induced waves or lake turnover may erode the FFT-water interface, as Adu-Wusu et al. (2001); Catalan and Yanful (2002), and Kachhwal et al. (2011) observed the erosion and resuspension of soft tailings stored under water caps. Thus, fluid movement in the lake could cause mixing within the tailings, which would create an additional form of fluid movement or advective mass transport. This mixing may only occur seasonally, for example, in the fall when the lake undergoes turnover, and would disturb the dominant form of mass transport occurring throughout the remainder of the year.

This study will provide valuable insight on the performance of end pit lakes as an oil sands reclamation strategy by characterizing the dominant mechanisms for heat and mass transport across the FFT-water interface. An understanding of these processes during the early stages of end pit lake development is essential for assessing the geochemical evolution of FFT, and the potential containment and isolation of FFT through the use of end pit lakes. When combined with biogeochemical analysis of the FFT pore water characteristics (e.g. Dompierre et al. 2016), findings from this study will assist in the development of monitoring and management plans for future end pit lakes.

2. Site Description

The first end pit lake was established at the Mildred Lake Mine approximately 35 km north of Fort McMurray, Alberta, Canada (Fig. 1; Fig. 2). The mine site is located in a sub-humid continental climate region with short summers and long cold winters (Carey 2008). Minimum and maximum mean daily temperatures of -39.8 °C (January 18, 1996) and 26.3 °C (August 1, 2003), respectively, have been measured at the Mildred Lake weather station adjacent to the mine (Environment Canada 2015). The mean annual temperature is 1.0 °C (Environment Canada 2015).

Operations at the Mildred Lake Mine began in 1978 when Syncrude Canada Ltd. commenced surface mining of oil sands ore. The oil sands ore is from the McMurray Formation, and generally contains an average of 12 % (w/w) bitumen (long chain hydrocarbons), 3 to 6 % (w/w) water, and 84 to 86 % (w/w) solids, comprised of quartz sand with a small clay fraction (Chalaturnyk et al. 2002). Bitumen is extracted from the ore by adding hot water to decrease the bitumen viscosity and caustic (NaOH) to disperse the clay particles (Caughill et al. 1993; Masliyah et al. 2004). The resulting bitumen froth is separated for upgrading and the remaining sand-clay slurry is pumped to tailings impoundments, for example the Mildred Lake Settling Basin, for storage. The current mine site and tailings impoundment locations are shown in Fig. 2.