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Rare earth element abundances and behaviour in oil sands froth treatment tailings

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Introduction

Froth treatment tailings (FTT) are one of three major waste streams produced at oil sands mining operations in the Athabasca Oil Sands Region (AOSR), in northern Alberta, Canada. This material is enriched in high-density (e.g., Ti- and Zr-bearing oxides) and acid-generating minerals (e.g., pyrite). Accordingly, studies characterizing FTT have focused on recovery of Ti and Zr minerals (Liu et al., 2006) and, more significantly, the potential for acid generation and metal(loid) release (Ferry et al., 2025; Kuznetsov et al., 2015; Lindsay et al., 2019). Rare earth elements (REEs) have also been observed in elevated concentrations, relative to oil sands ore, in FTT (Lindsay et al., 2019), but little is known regarding REE-hosting phases and controls on REE mobility in FTT, limiting insights into the feasibility of REE recovery and environmental implications related to REE behaviour in an oil sands mine-closure environment. Further, it is unclear how long-term storage and closure strategies for FTT will influence REE mobility; current closure plans for FTT involve terrestrial storage beneath a soil reclamation cover, which could affect REE behaviour by altering biogeochemical reactions, kinetics, and mass transport. These knowledge gaps are significant from both economic and environmental standpoints, as recent studies have highlighted the importance of developing underexploited sources of REEs, including mine wastes (Filho et al., 2023; Gaustad et al., 2021), while others have investigated REEs as an emerging mining-related contaminant, posing substantial detriment to receiving aquatic resources (Guo et al., 2025; Liu et al., 2019). This work seeks to generate understanding into the concentrations and geochemical behaviour of REEs in FTT, providing important context for understanding any economic potential of FTT as a secondary REE source, and the long-term storage and environmental suitability of FTT in various reclamation scenarios.

Methods

This work incorporated both field- and laboratory-based components. Field-scale lysimeters containing replicates of variably weathered FTT (i.e., non-weathered, partially weathered, and weathered), with and without a reclamation soil cover, installed at an oil sands mine in northern Alberta, Canada were used to interpret REE behaviour across various weathering and potential reclamation conditions. Annual core sampling (2022–2025) from the lysimeters supported solid-phase analyses and pore-water extraction using a centrifugation-based technique. Additionally, wells installed in each lysimeter allowed seepage-water samples to be collected at regular intervals. To investigate the influence of pH on REE mobility from FTT, we used column experiments, with the experimental setup outlined in detail in Ferry et al. (2025). Briefly, acidic input solution (0.05 M H_2SO_4) was passed through FTT-bearing columns, resulting in a decrease in effluent pH from 7 to ~2 over the course of the experiment. Effluent was sampled from a flow-through cell for each pore volume, which roughly corresponded to a three-day sample interval. Seepage-water, pore-water, and effluent samples were analyzed for pH, electroconductivity (EC), and reduction-oxidation potential (Eh) immediately after extraction and were analyzed for major, minor, and trace elements (including REEs) using ion chromatography (IC), inductively coupled plasma optical emission spectrometry (ICP-OES), and inductively coupled plasma mass spectrometry (ICP-MS), respectively.

Results

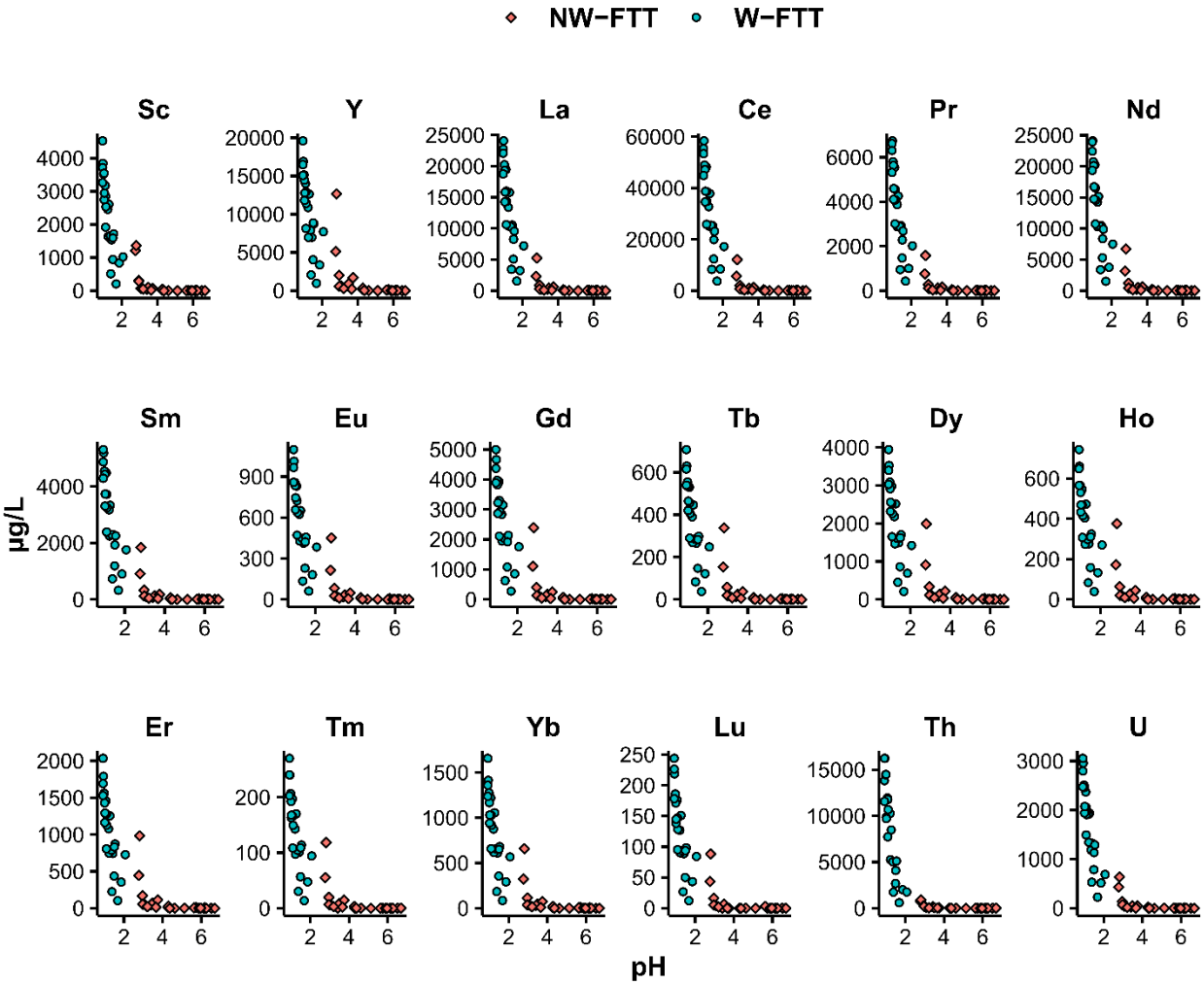


Figure 1: *REE concentrations in pore water from variably weathered FTT. Note: NW-FTT = Non-weathered FTT; W-FTT = Weathered FTT*

The behaviour and mobility of REEs from FTT is largely controlled by pH-dependent interactions (Figure 1). All REEs displayed far higher concentrations under acidic conditions in weathered FTT, as has been reported for REEs in systems affected by acid rock drainage (ARD) (Lozano et al., 2019; Stewart et al., 2017; Verplanck et al., 2004). This result is not surprising; REEs are typically present in the +3-oxidation state and, therefore, become mobilized in acidic conditions as mineral surfaces become more positively charged. In addition, secondary minerals, which are known to be important in REE attenuation, are more soluble at low pH, resulting in enhanced REE mobility (Ayora et al., 2016; Stewart et al., 2017).

The maximum REE concentrations observed in weathered FTT are notable, especially when compared with typical REE concentrations observed in ARD-affected surface waters (Noack et al., 2014; Stewart et al., 2017; Vass et al., 2019). For example, Nd, Pr, and Dy, three REEs of critical importance for the energy transition, reached concentrations of 24.1, 6.70, and

3.9 mg L^{-1}, respectively, while Ce concentrations reached a maximum of 58.39 mg L^{-1}. Average REE concentrations observed at values exceeding 1 mg L^{-1} in weathered FTT samples followed the general trend: Ce > Nd, La > Pr, Sm, Sc > Er, Yb, largely in agreement with the trend defined by Lindsay et al. (2019) for REE concentrations in FTT solids. Further, Lindsay et al. (2019) postulated that monazite could be an important REE-hosting mineral in FTT, although other phosphate minerals (e.g., xenotime) may also play a role; the relatively elevated concentrations of Ce, Nd, and La found here are also suggestive of REE associations with monazite in FTT.

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