Developing integrated understanding of the geochemical evolution of an oil sands froth treatment tailings deposit

Matthew Lindsay,[1] Eduardo Marquez,[1,2] Sanaz Hasani,[1] Josh Paulsen,[1,3] Drake Meili,[1,3] Stuart Ferry,[1] Jake Marchi[1,4]

[1]Department of Geological Sciences, University of Saskatchewan, Saskatoon, Canada

also: [2]SRK Consulting, [3]Okane Consultants, [4]AtkinsRéalis

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Oil Sands Deposits

- oil sands deposits contain 166B barrels of proven reserves
- hosted in sands and sandstones of the Cretaceous McMurray formation
- ore comprised of:
  - bitumen (8–15% w/w)
  - water (2–5% w/w)
  - solids (80–90% w/w)
- approximately 3.4% (4800 km^2) of deposit area accessible by surface mining
  - active mining footprint > 1000 km^2 (2023)

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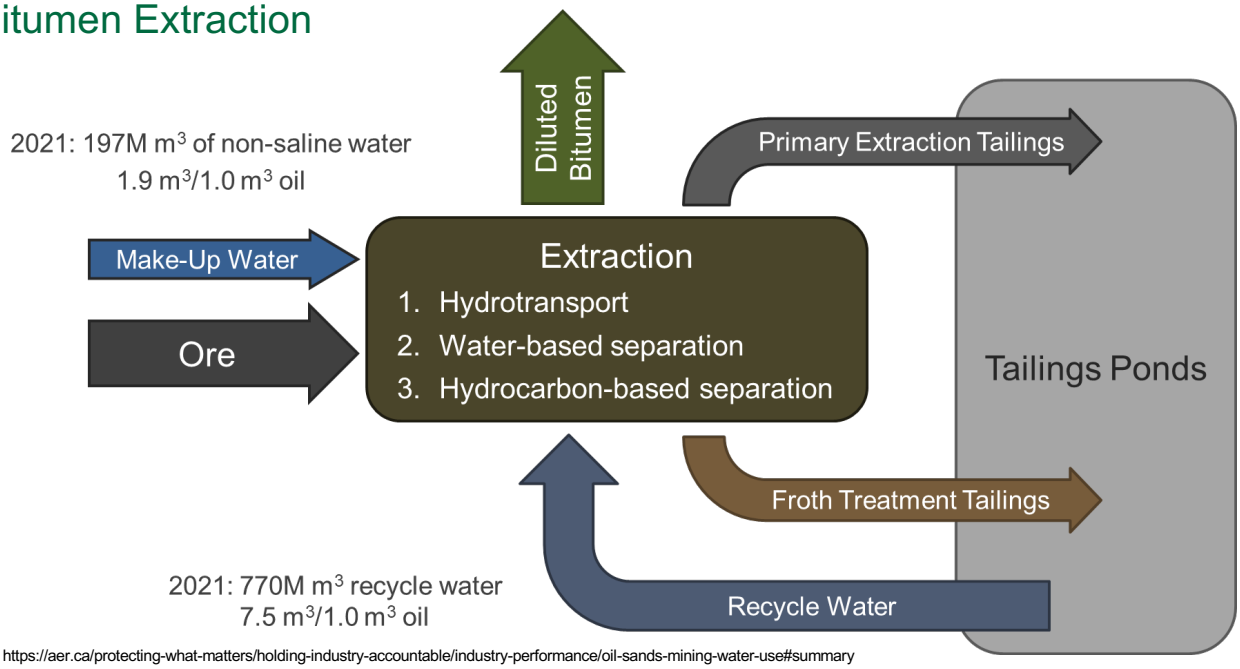
Canada has 3rd largest oil reserves in the world, the majority in oil sands

Oil sands account for large majority (~97%) of proven Canadian oil reserves

Only a small area of deposits (~3.4 %) accessible through surface mining

Bitumen Extraction



Data: https://aer.ca/protecting-what-matters/holding-industry-accountable/industry-performance/oil-sands-mining-water-use#summary
Figure after: Mikula (2012) *In:* Restoration and Reclamation of Boreal Ecosystems. Ch. 6, pp. 103-122.

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Make-up Water

- 63% from Athabasca R. (200 to >1000 m3/s)
- 37% from on-site sources (groundwater, surface water)

Froth Treatment Tailings (FTT)

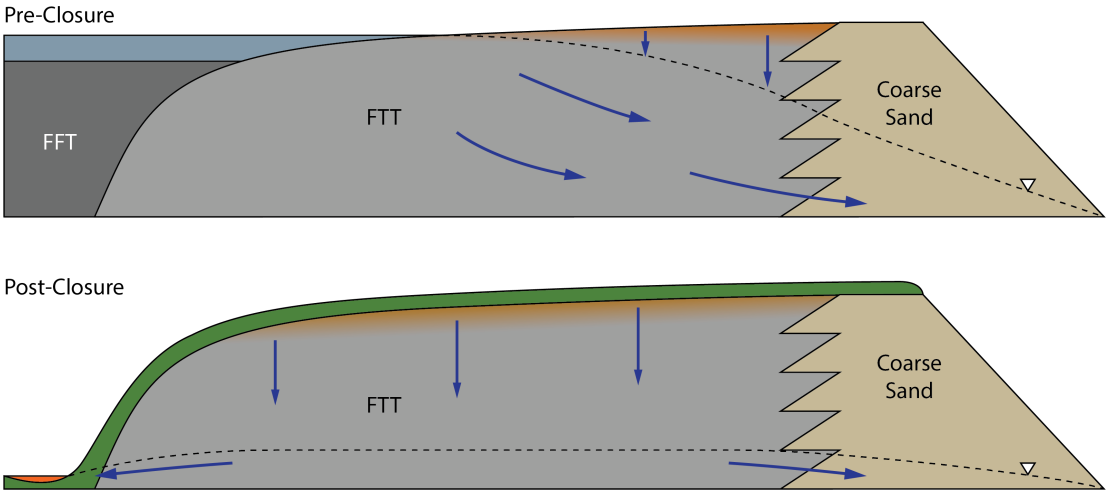
- produced during hydrocarbon-based gravity separation
  - diluent hydrocarbons added to liberate entrained solids and residual water
  - elevated oxide, carbonate, and sulfide mineral contents relative to other tailings
- sub-aerial or sub-aqueous deposition within engineered tailings facilities
  - hydraulic segregation influences FTT deposit characteristics
    - geochemistry
    - mineralogy
    - hydrogeology

~5 % (v/v) of total tailings production at Syncrude Base Mine operation

Geochemical Considerations

- geochemical evolution variable:
  - ore deposit heterogeneity
  - naphthanic versus parrafinic solvent
  - sub-aerial versus sub-aqueous deposition
- potential environmental risks include:
  - acid generation
  - metal(loid) release
  - biogenic gas production
- potential mitigation considerations:
  - acid neutralization reactions
  - microbial sulfate reduction
  - oxygen consumption reactions

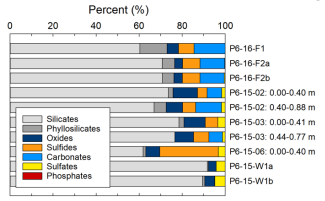
Toward Integrated Understanding

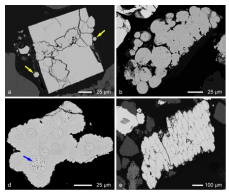


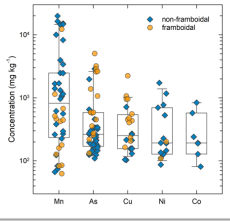
Note: Diagram intended for illustrative purposes only. Does not accurately represent material placement, landform scale, closure design, etc..

Characterizing Source Terms

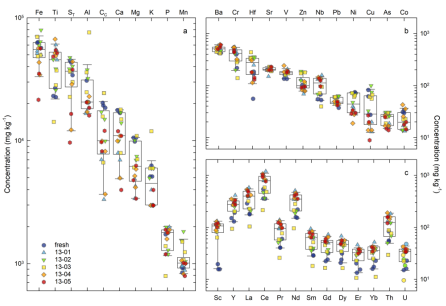
mineralogy/mineral chemistry



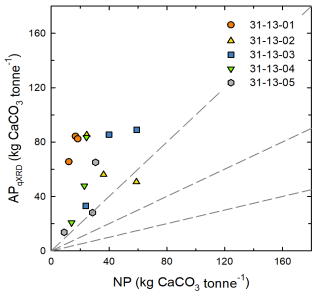




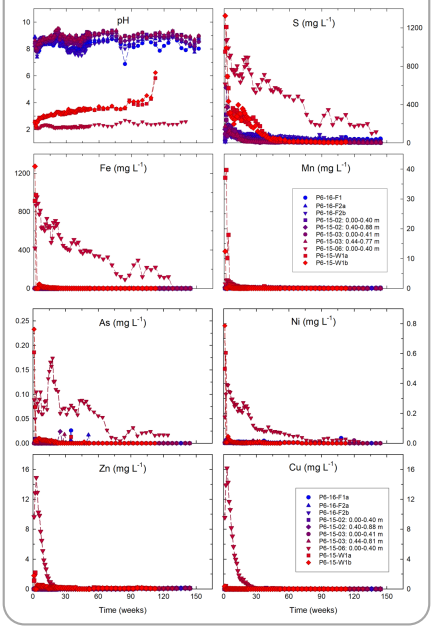
geochemistry



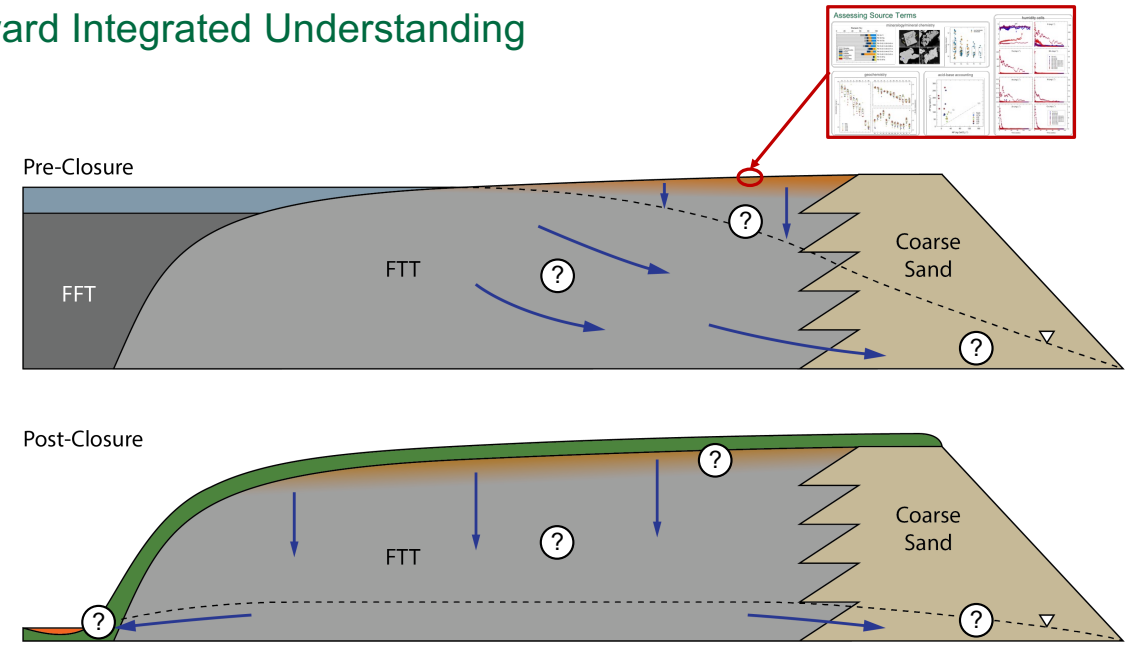
acid-base accounting



humidity cells



Toward Integrated Understanding



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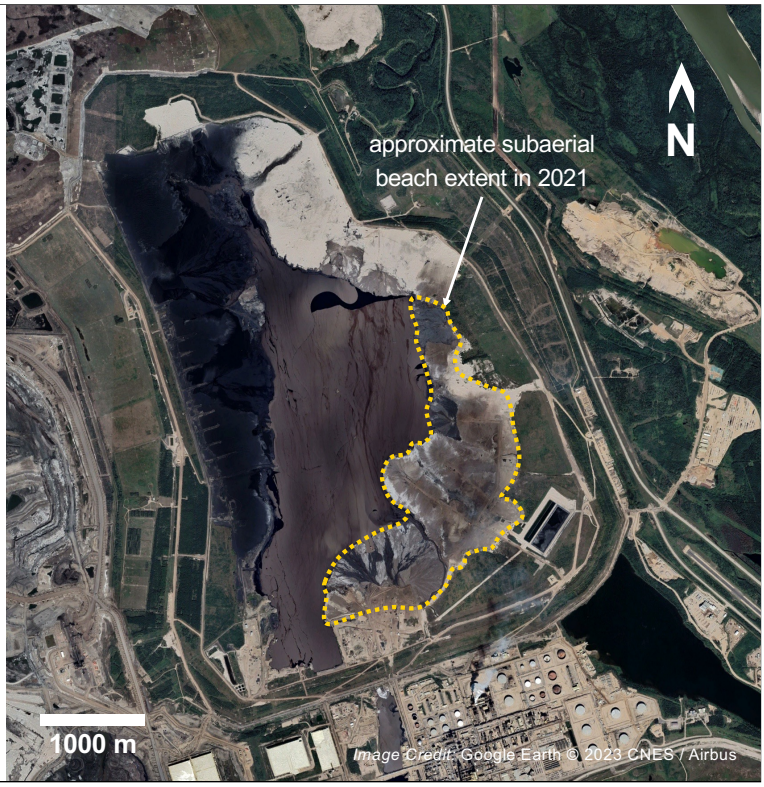
Source-pathway-receptor

Source is the entire deposit

Source changes over time and with management/mitigation

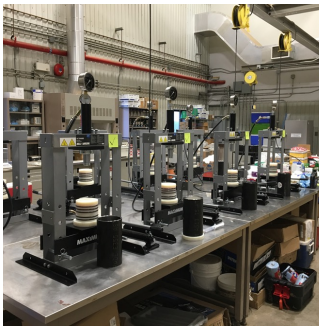
Plant 6 FTT Deposit

- located in Mildred Lake Settling Basin at Syncrude's Base Mine
  - ~5 vol. % of total tailings production
- variably saturated beach deposit
  - ~2.5 km^2 sub-aerial extent
  - < 45 m total thickness
- variable water table depth
  - currently 0 to > 10 m below surface
  - post-closure depth will be deeper

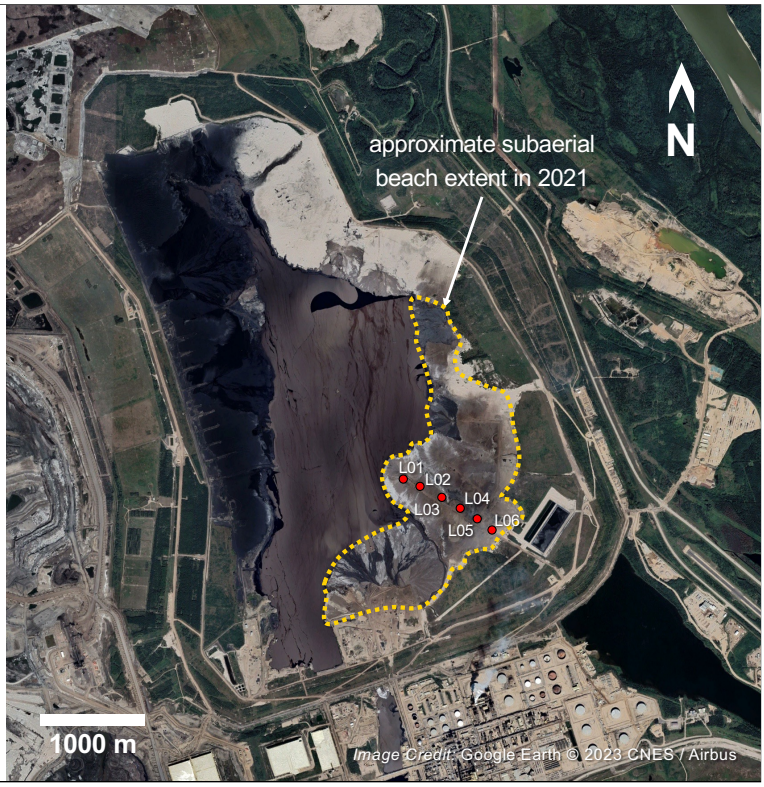


Plant 6 FTT Deposit

- continuous sonic core sampling
  - 6 locations cored to refusal
  - porewater extracted for analysis
  - solids sub-sampled for analysis



Amphibious sonic drill rig (left) and porewater squeezing setup (right).

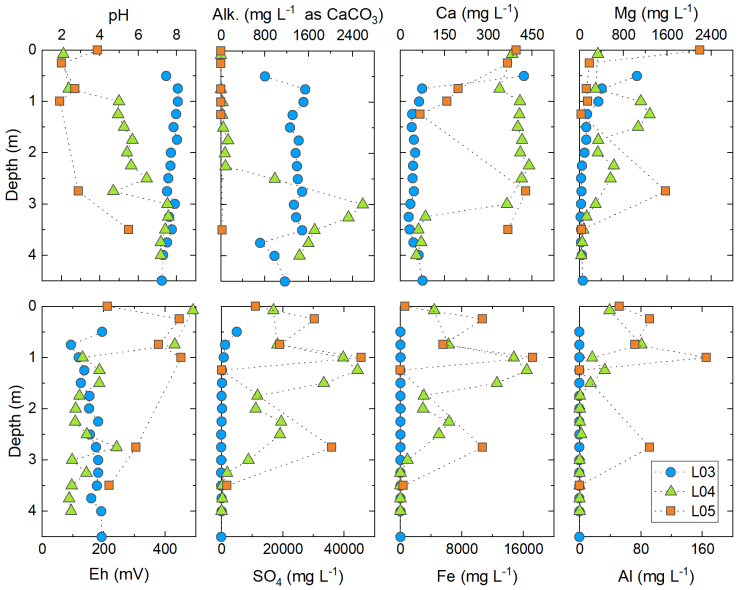


Amphibious sonic rig

FTT Beach: Porewater Chemistry

MSc research by J. Paulsen

- localized low pH conditions observed:
  - L04: upper 1 m
  - L05: upper 3 m
- low pH can correspond to:
  - high Fe, Al, and SO4
  - elevated Ni, Co, Zn, As, Cu



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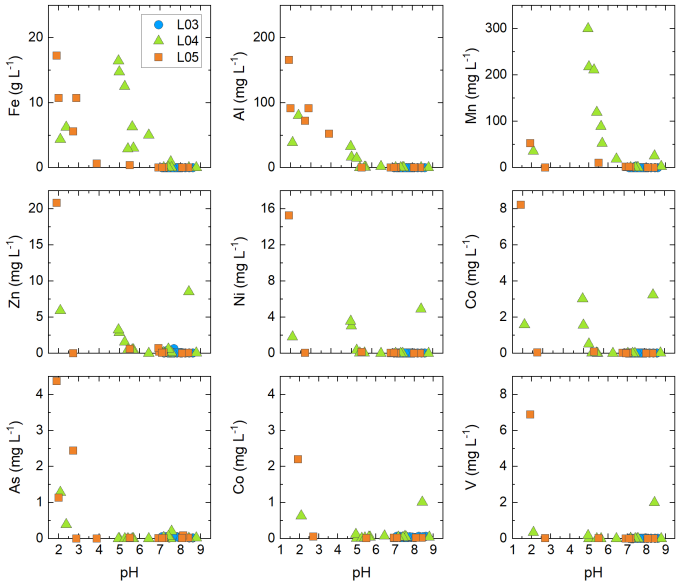
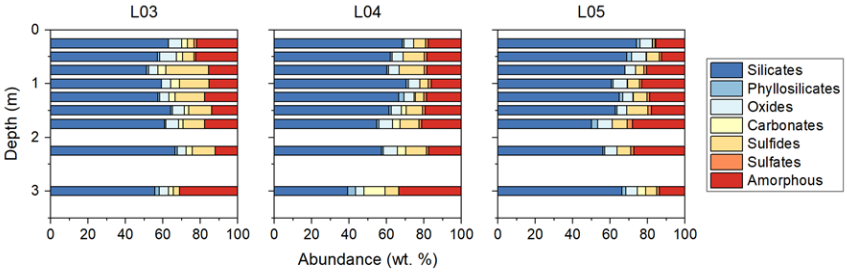
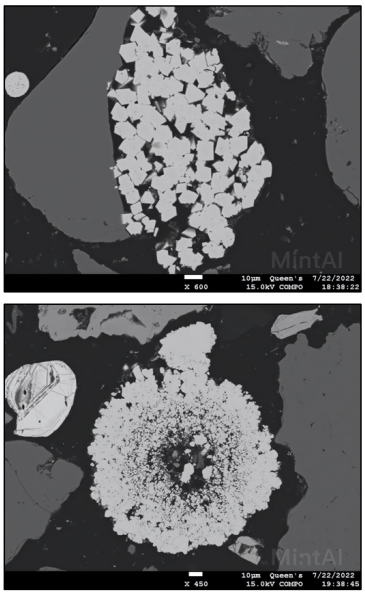


MSc research by J. Paulsen & D. Meili

FTT Beach: Mineralogy

- mineral assemblage dominated by silicates
  - quartz >>> tourmaline > zircon, feldspar
- various phyllosilicates, oxides, and phosphates
  - kaolinite, chlorite, illite, anatase, rutile, apatite, monazite/xenotime
- variable sulfide and carbonate contents
  - pyrite plus minor marcasite with minor/trace As, Co, Ni, Cu contents
  - siderite > calcite, dolomite, ankerite

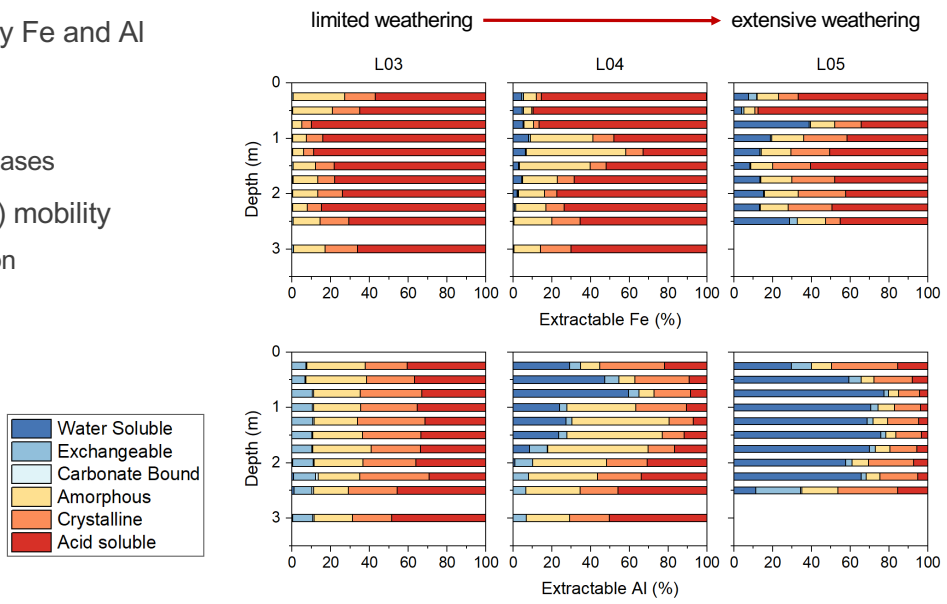




FTT Beach: Geochemistry

MSc research by J. Paulsen & D. Meili

- accumulation of secondary Fe and Al phases during weathering
  - water soluble phases
  - amorphous/crystalline phases
- implications for metal(loid) mobility
  - adsorption/co-precipitation



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Ksp values:

Jarosite: 10^-14.8

Calcite: 10^-8.48

Gypsum: 10^-4.61

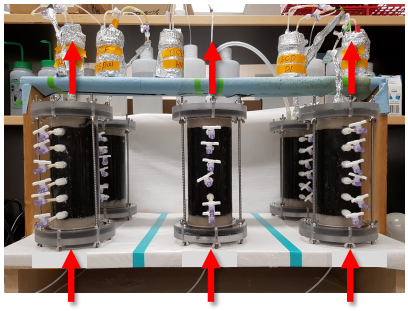
Alunite: 10^-1.41

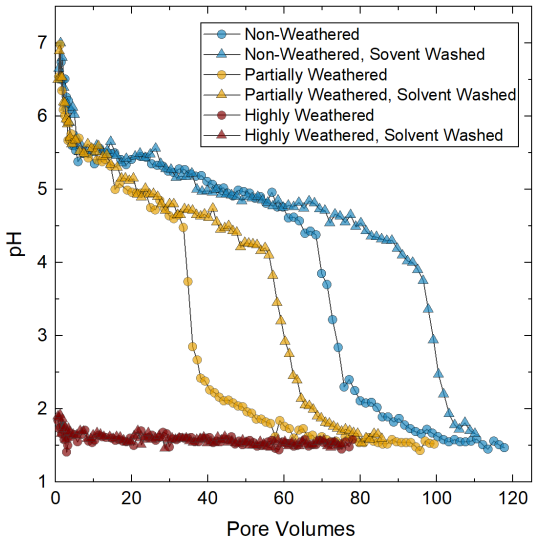
Hydrobasaluminite: 10^-24

MSc research by S. Ferry

Laboratory Experiments: Acid Neutralization

- column experiments performed to better understand influence of pH on metal(loid) release
- effluent pH dependent on two key factors:
  - initial weathering extent
  - residual hydrocarbons

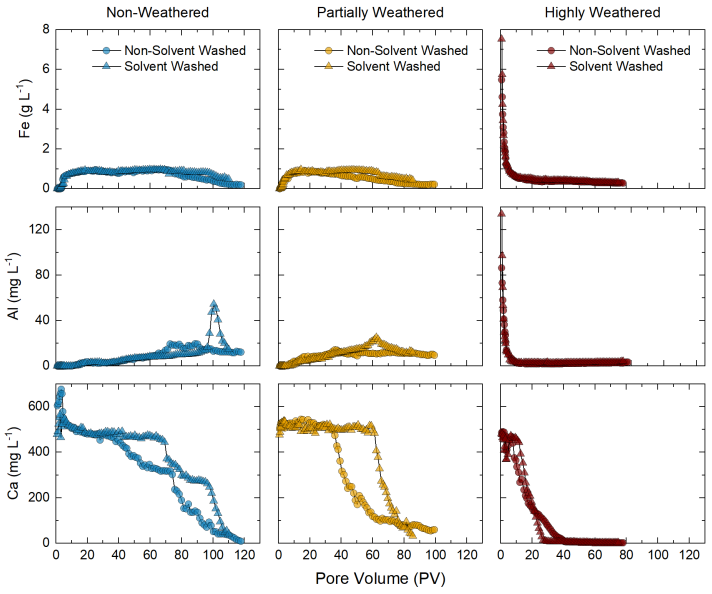




MSc research by S. Ferry

Laboratory Experiments: Acid Neutralization

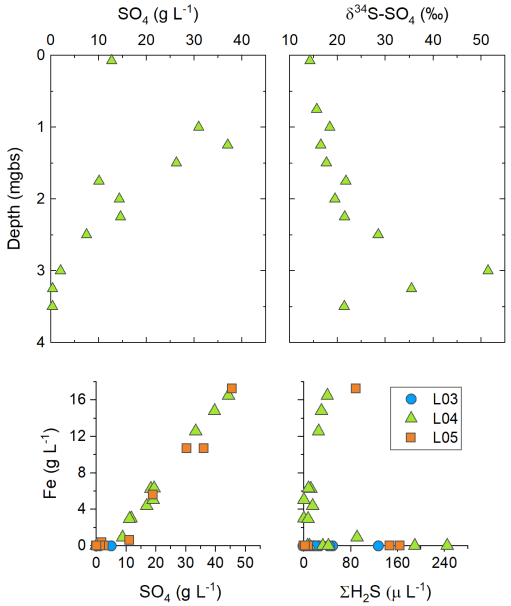
- initial Fe and Al release from highly weathered columns
  - dissolution of weathering products (e.g., Fe/Al hydroxysulfates)
- element release/mobility influenced by pH-dependent reactions
  - dissolution-precipitation
  - adsorption-desorption



Laboratory Experiments: Sulfate Reduction

MSc research by J. Marchi

- strong evidence of microbial sulfate reduction in FTT beach deposit
- generates H_2S/HS^- and promotes precipitation of metal sulfide phases
- can contribute to sulfate and metal attenuation in tailings deposits



Environ. Sci. Technol. **2009,** *43,* 7086–7091

Managing Pore-Water Quality in Mine Tailings by Inducing Microbial Sulfate Reduction

MATTHEW B.J. LINDSAY,† DAVID W. BLOWES,*,† PETER D. CONDON,† AND CAROL J. PTACEK†

Department of Earth and Environmental Sciences, University of Waterloo, 200 University Ave. W., Waterloo, ON, N2L 3G1, Canada, and Environmental Department, Hecla Greens Creek Mining Company, P.O. Box 32199, Juneau, Alaska 99803

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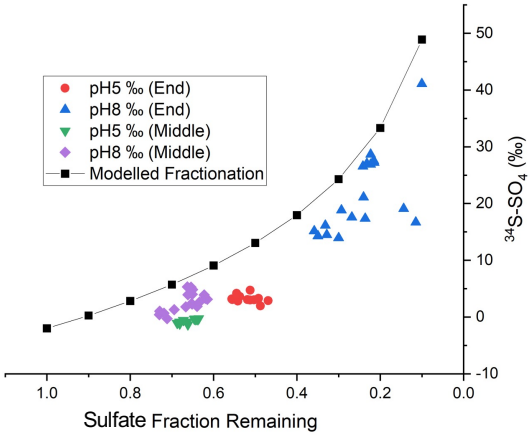
metals and metalloids, including Fe(II), Zn, As, Sb, and Tl, may remain soluble at near-neutral pH given appropriate redox conditions (*5*−*7*). Management of drainage quality is therefore essential during tailings placement and following closure.

Conventional active treatment methods often require substantial long-term energy, reagent, labor, and consequently, financial inputs (*8*). In contrast, passive methods, which minimize the transport and subsequent discharge of sulfide oxidation products, may reduce environmental and financial liabilities associated with mineral extraction. Strategies for passive management of tailings drainage water quality are generally categorized as either source control or migration control (*9*). Source control techniques, such as subaqueous disposal, inhibit oxidation by minimizing exposure of sulfide minerals to oxygen. These techniques can, however, be impractical to implement during active tailings deposition. Furthermore, source control generally disregards dissolved S, metals, and trace elements contributed by

Laboratory Experiments: Sulfate Reduction

MSc research by J. Marchi

- laboratory batch and column experiments revealed robust sulfate reduction within Plant 6 FTT deposit
- metal(loid) mobility attributed to metal sulfide precipitation and other processes



PhD research by E. Marquez

Field Experiments: Reclamation Soil Covers

- geochemical responses to soil covers dependent upon tailings characteristics
  - weathered tailings respond differently than non-weathered tailings
- lysimeter experiments underway to assess influence of weathering history and soil covers
  - geochemical, mineralogical, hydrogeological, and microbial data being collected
- complementary laboratory column experiments also underway

Non-Weathered FTT

Uncovered

Covered

Partially Weathered FTT

Uncovered

Covered

Highly Weathered FTT

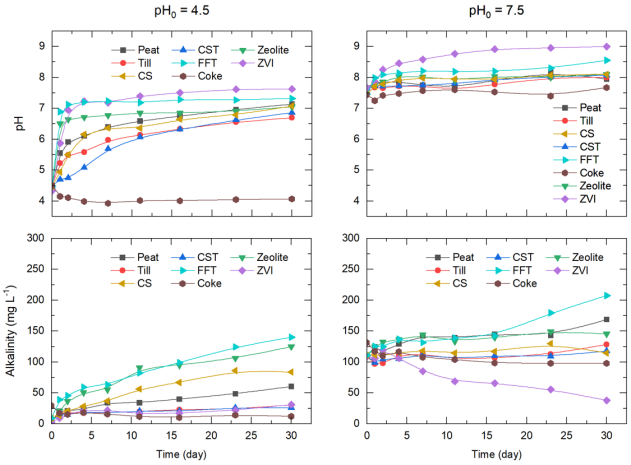
Uncovered

Covered

PhD research by S. Hasani

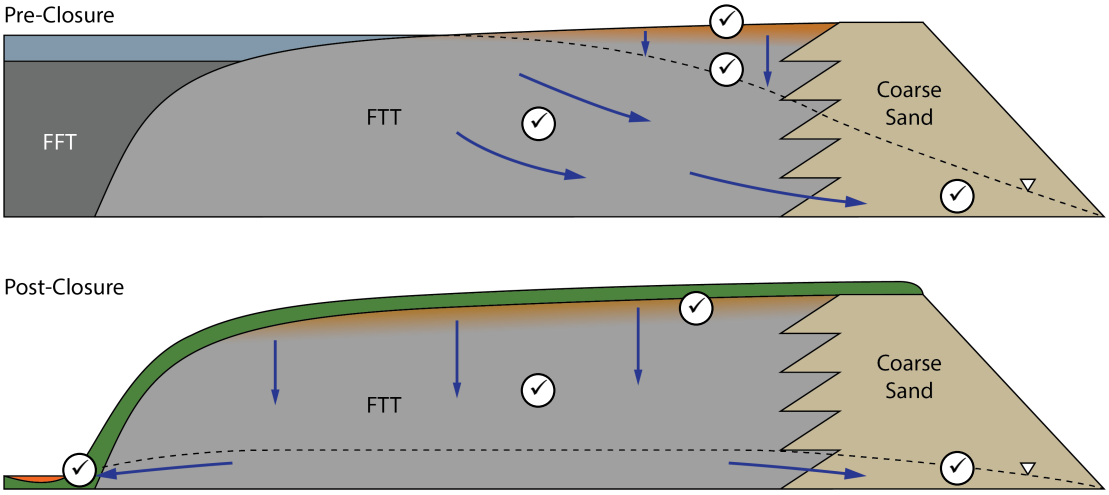
Laboratory Experiments: Attenuation Processes

- other mine materials may contribute to attenuation of oxidation products
  - examples: till, peat, shale (CS), fluid tailings (FFT), coarse tailings (CST)
- laboratory batch and column experiments are underway to assess attenuation potential



Toward Integrated Understanding

- How do we connect the “dots”?



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Toward Integrated Understanding

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Reactive transport modelling of porewater geochemistry and sulfur isotope fractionation in organic carbon amended mine tailings

Andrew T. Craig [a,*], Alexi Shkarupin [b], Richard T. Amos [a], Matthew B.J. Lindsay [c], David W. Blowes [d], Carol J. Ptacek [d]

[a] Department of Earth Sciences, Carleton University, Ottawa, Ontario, Canada
[b] Department of Earth and Environmental Sciences, University of Ottawa, Ottawa, Ontario, Canada
[c] Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan, Canada
[d] Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Ontario, Canada

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Sodium transport and attenuation in soil cover materials for oil sands mine reclamation

Colton J. Vessey[a], Matthew B.J. Lindsay[a,*], S. Lee Barbour[b]

[a] Department of Geological Sciences, University of Saskatchewan, Saskatoon, SK, S7N 5E2, Canada
[b] Department of Civil, Geological and Environmental Engineering, University of Saskatchewan, Saskatoon, SK, S7N 5A9, Canada

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ConeTec Investigations

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