The Diavik Waste-Rock Project: Factors controlling sulfide oxidation at the micro and macro scale.

21th ANNUAL BRITISH COLUMBIA-MEND ML/ARD WORKSHOP

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Vancouver

Richard Amos (Carleton University)

Jeff Langman, Sean Sinclair, David Wilson, Brenda Bailey, and David Blowes (University of Waterloo)

Andrew Krentz, Nate Fretz and Leslie Smith (University of British Columbia)

Nam Pham and David Sego (University of Alberta)

Canada Foundation for Innovation
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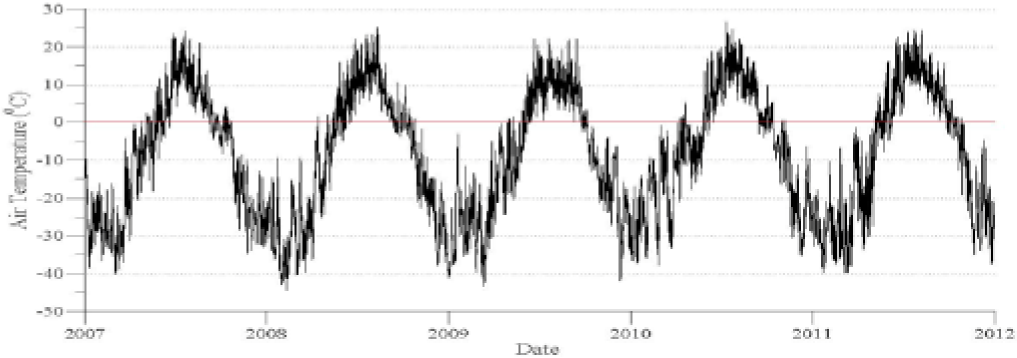
Site Location



Zone of continuous permafrost
MAAT ~ -9°C

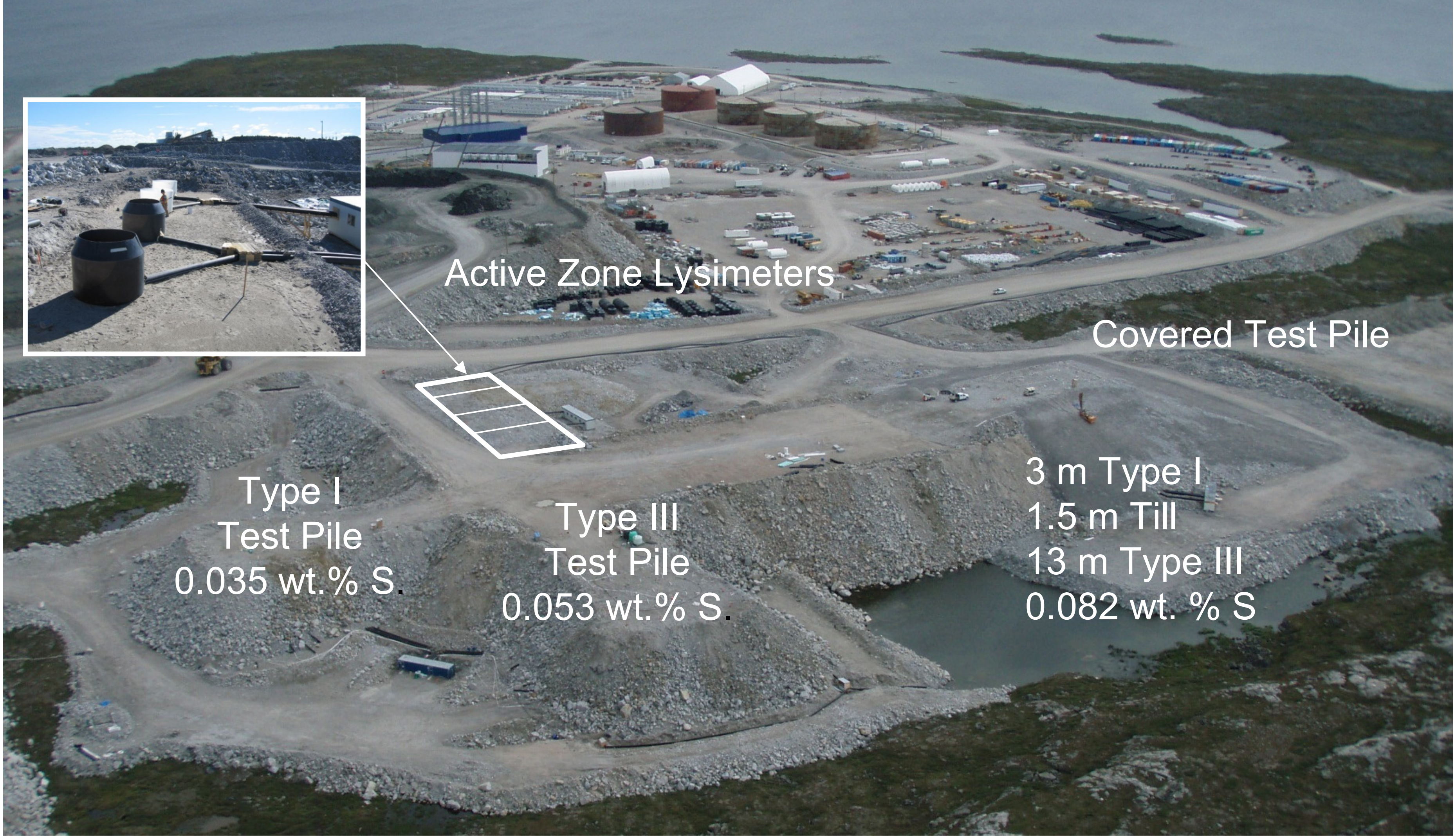
Research Goals – Sulfide Oxidation in a Permafrost Region

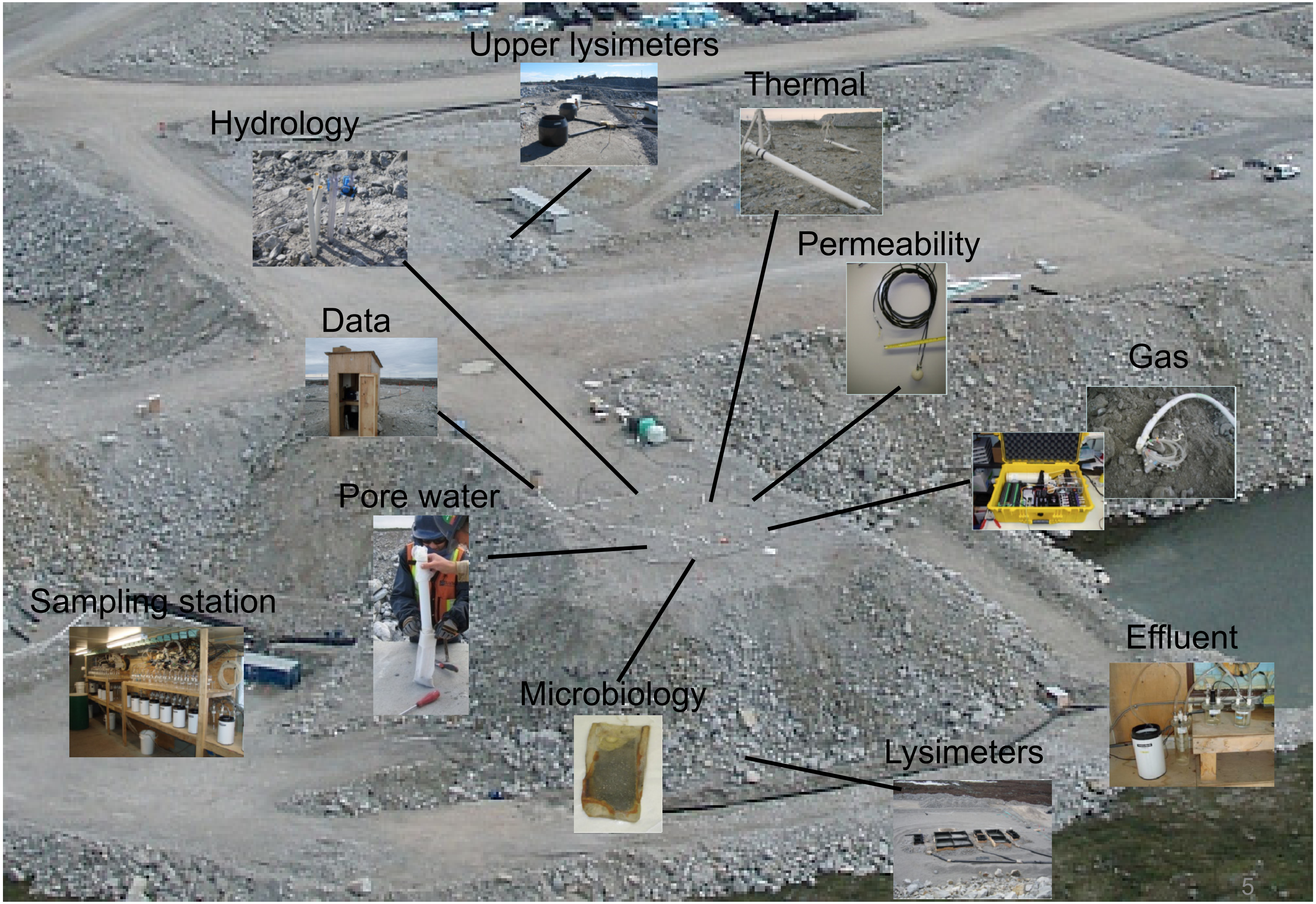
- Understand the geochemical, hydrological, and thermal conditions controlling the generation of acidic leachate from waste rock stockpiles in a permafrost environment

Research Goals: Micro- to Macro-Scale

- Scaling the temporal evolution of sulfide mineral weathering from laboratory to field systems
  - Improving the conceptual model
  - Developing more representative reactions rates

Test Piles Research Area

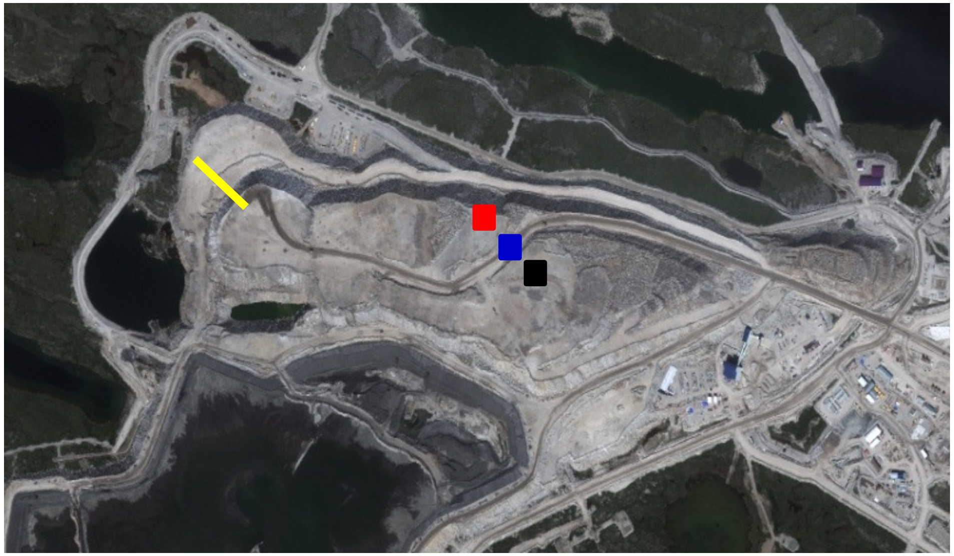



Upper lysimeters
Thermal
Hydrology
Permeability
Data
Gas
Pore water
Sampling station
Effluent
Microbiology
Lysimeters

Research Facilities

- Laboratory humidity cell experiments
  - 18 Cold room (4 °C)
  - 18 Room Temperature (22 °C)

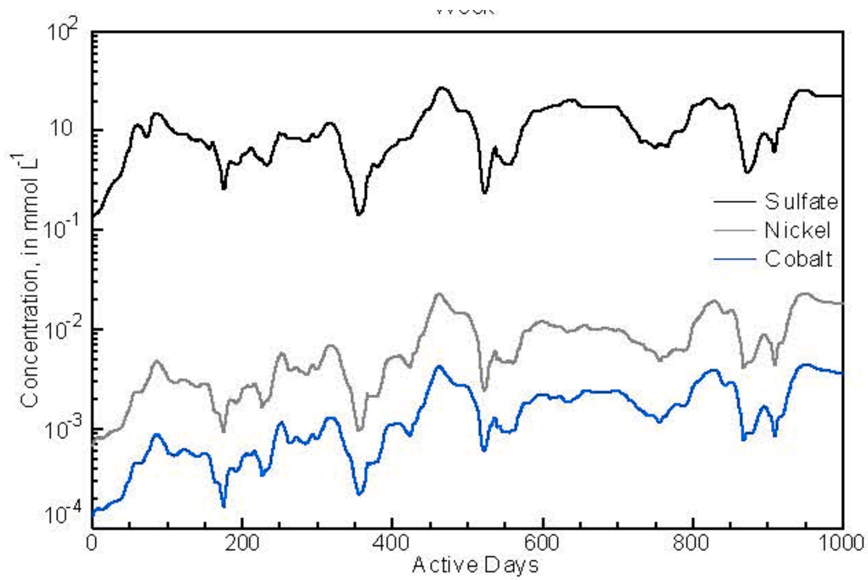
- Instrumented full-scale waste rock dump
  - 4 x 40 m vertical drill holes
  - 1 x 80 m vertical drill hole
  - horizontal instrument string



- ● (black) 3 drill holes
  - 32, 31 and 40 m deep
- ● (blue) 80 m drill hole
- ● (red) 40 m drill hole
- (yellow line) Horizontal Installation
  - 120m and 280 m

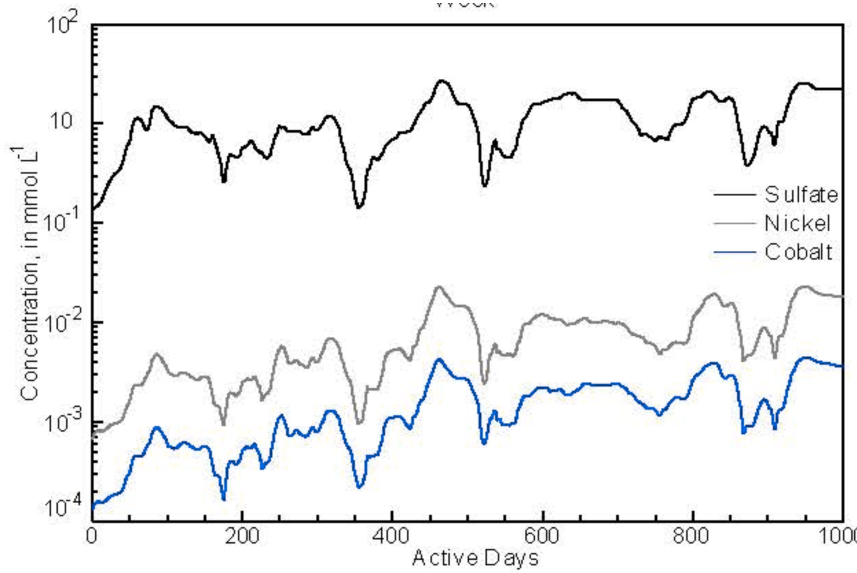
Mineral Weathering

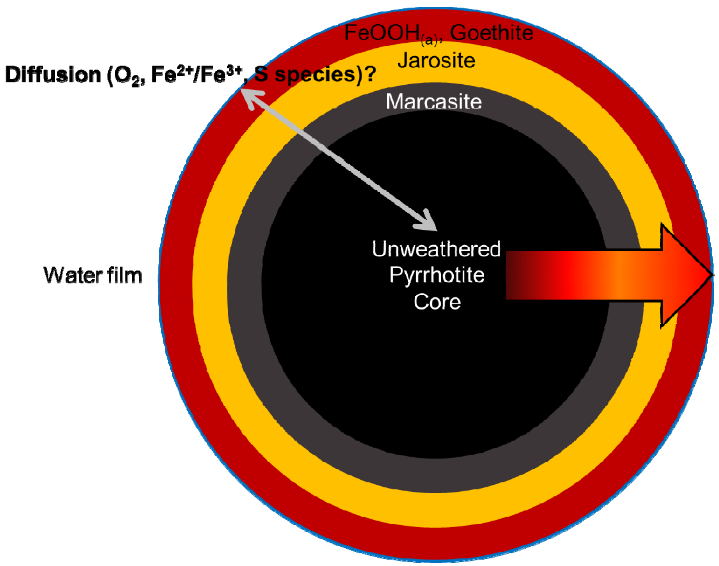
- We see this…



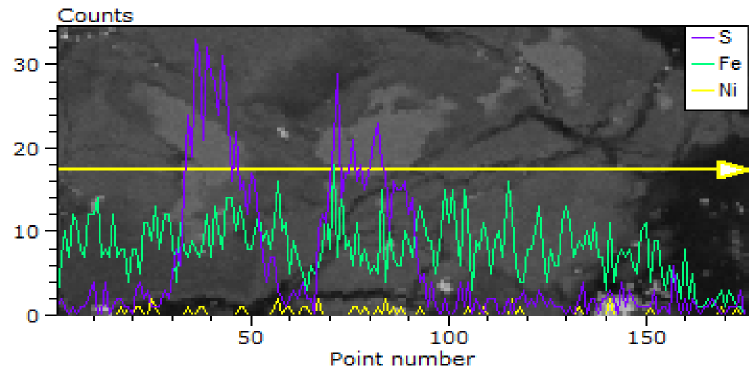
Mineral Weathering

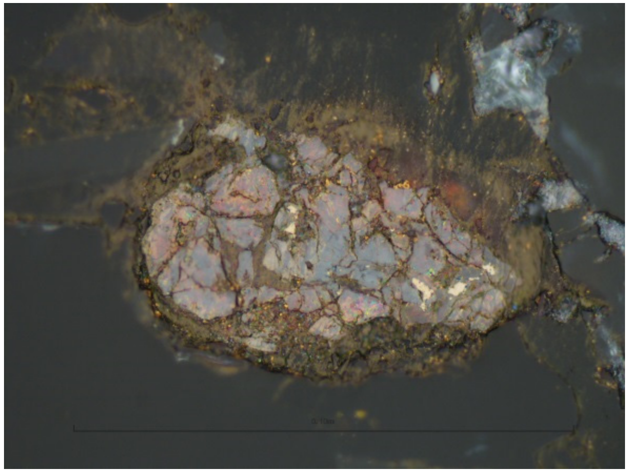
- and we want to envision this…



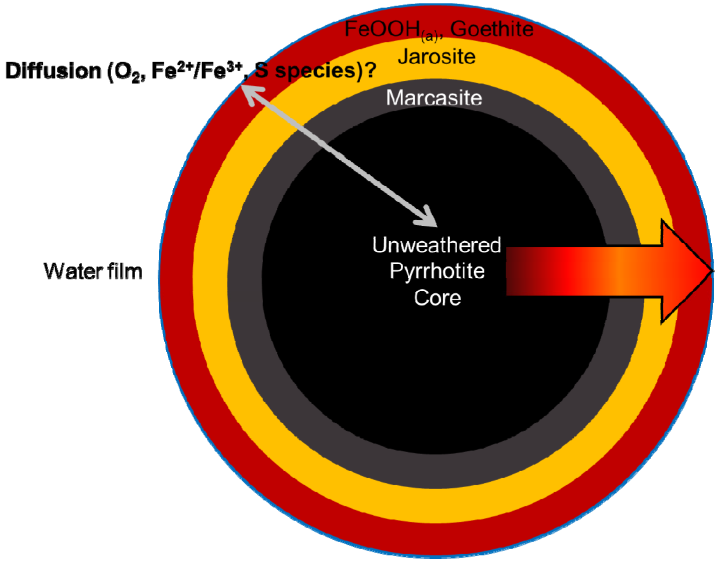


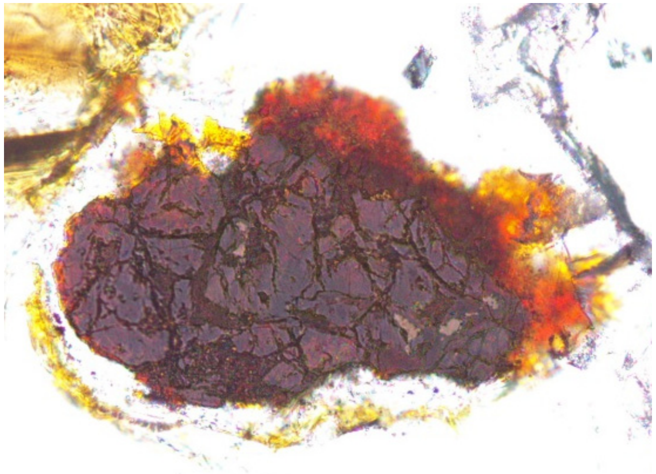
Mineral Weathering





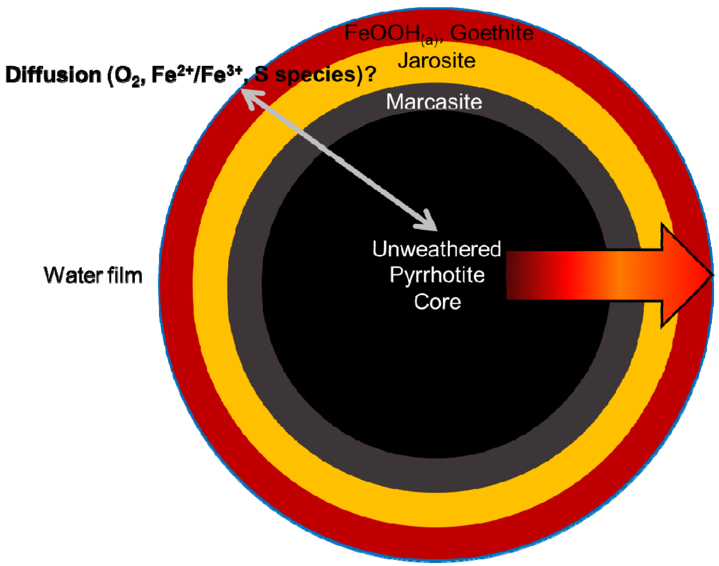
- but what we have is this.





Mineral Weathering

Need to correlate sulfur evolution with metal products



Fe oxides

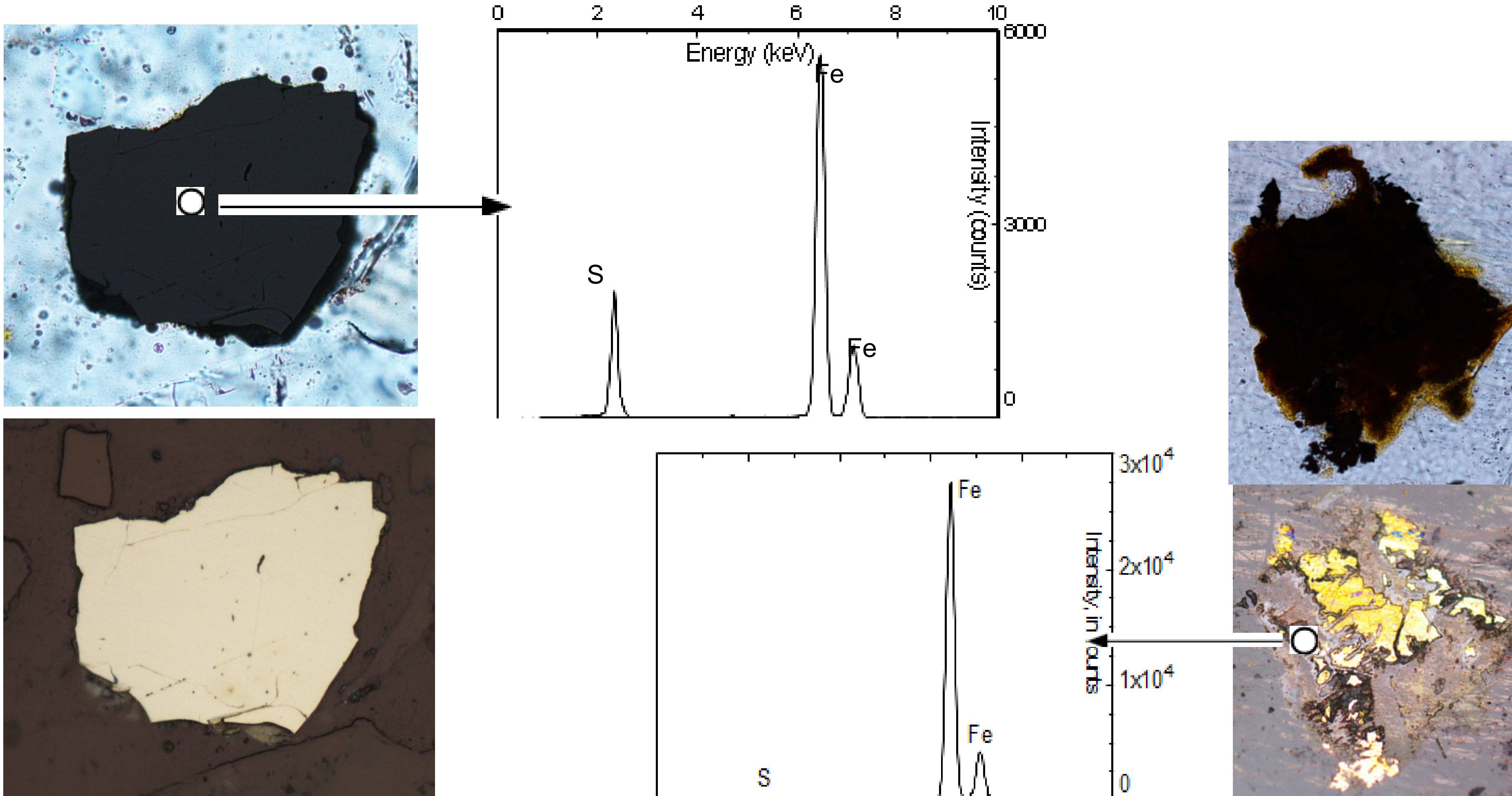
Fe (oxy)hydroxides (e.g., FeO(OH))

Intermediaries (other polysulfides, sulfite, thiosulfate, elemental S)

S-enriched layer (e.g., FeS_2)

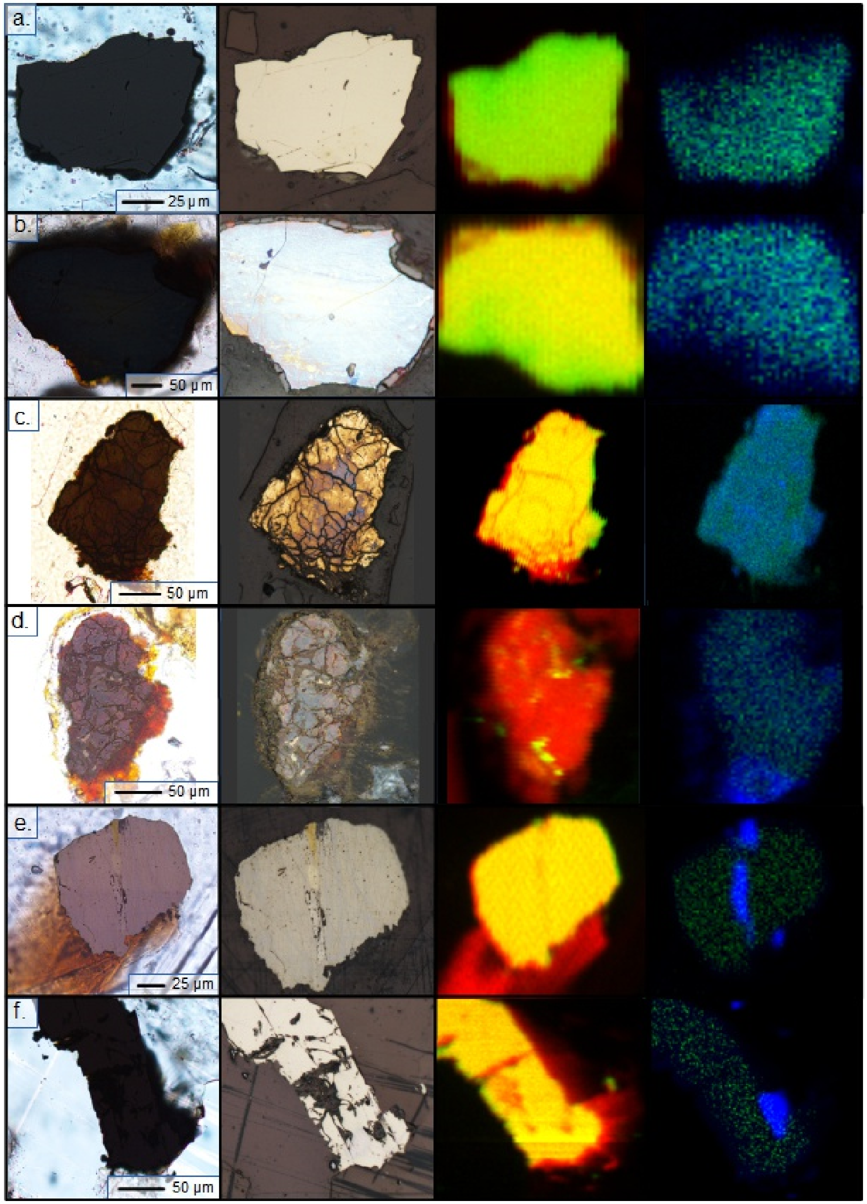
Unreacted pyrrhotite surface

Grain Scale Alteration



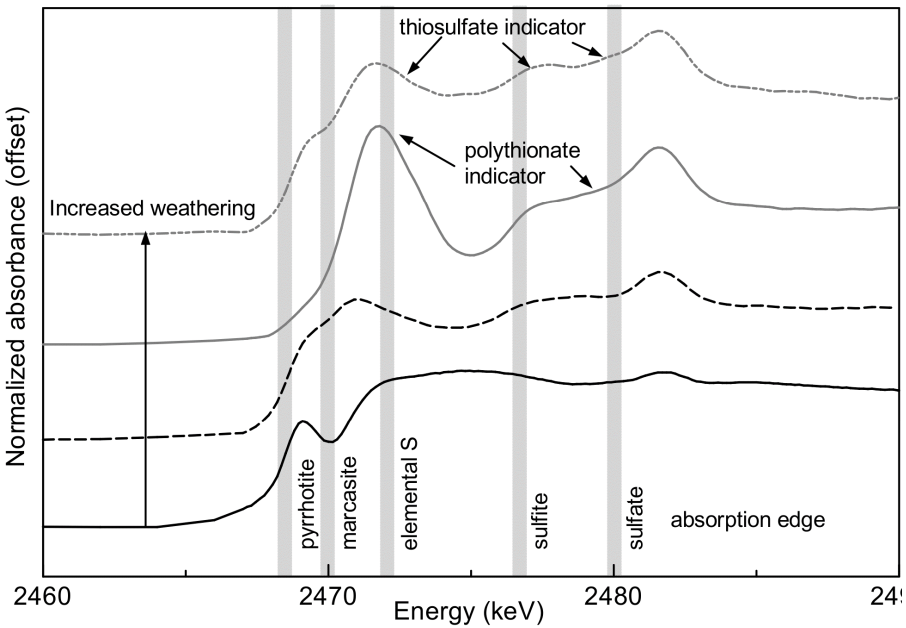
Element Relations

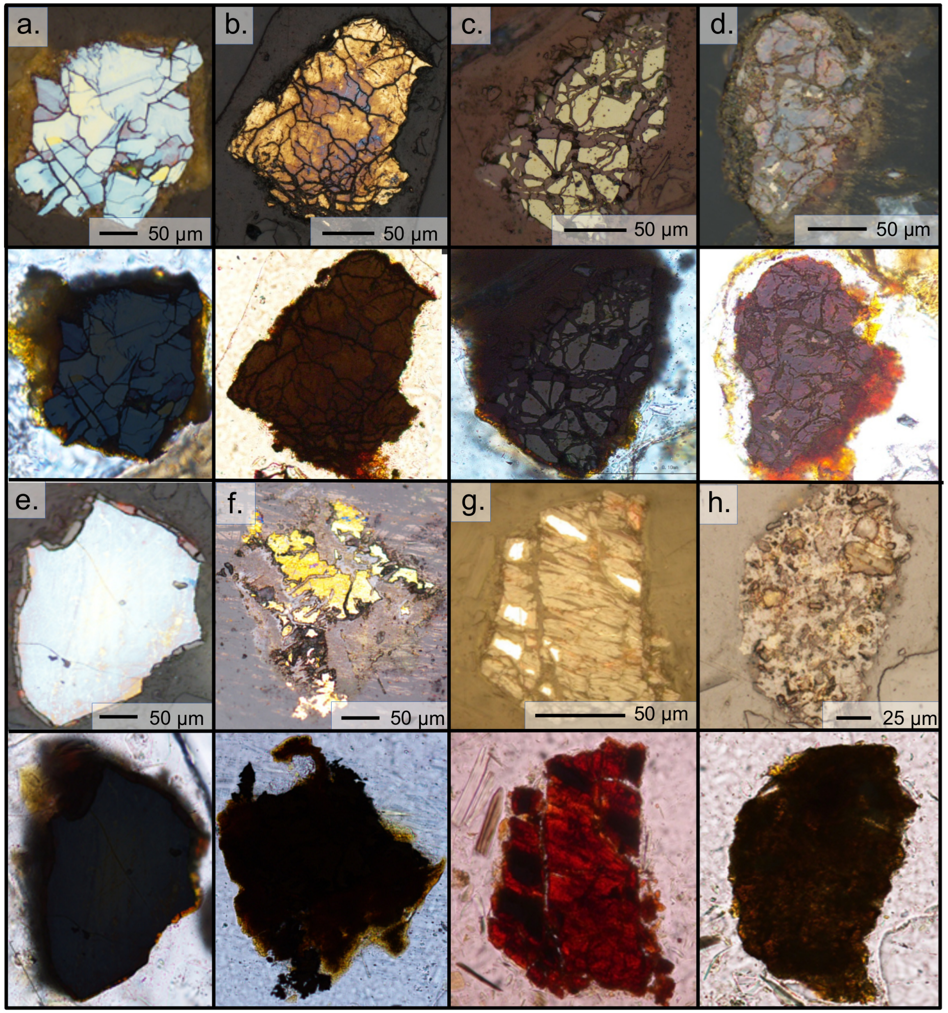
- Relation of Fe, Ni, and S within the grain system



Small Difference in Mineralogy and Changes in the Weathering Environment

- Strong differences in mineral oxidation with variations in weathering in the same climate

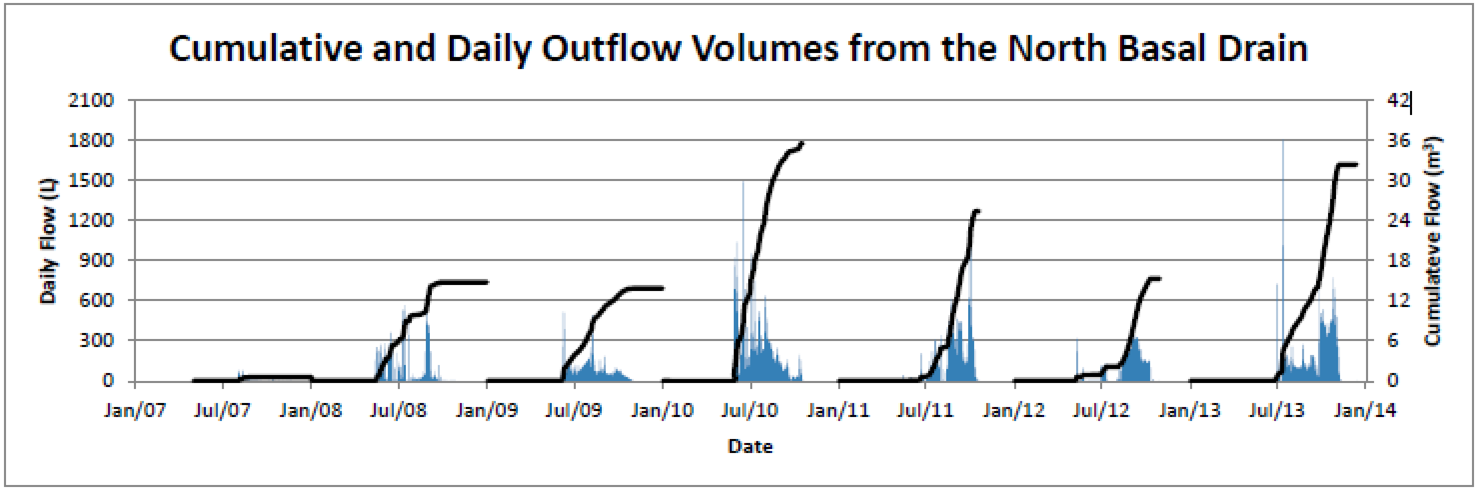


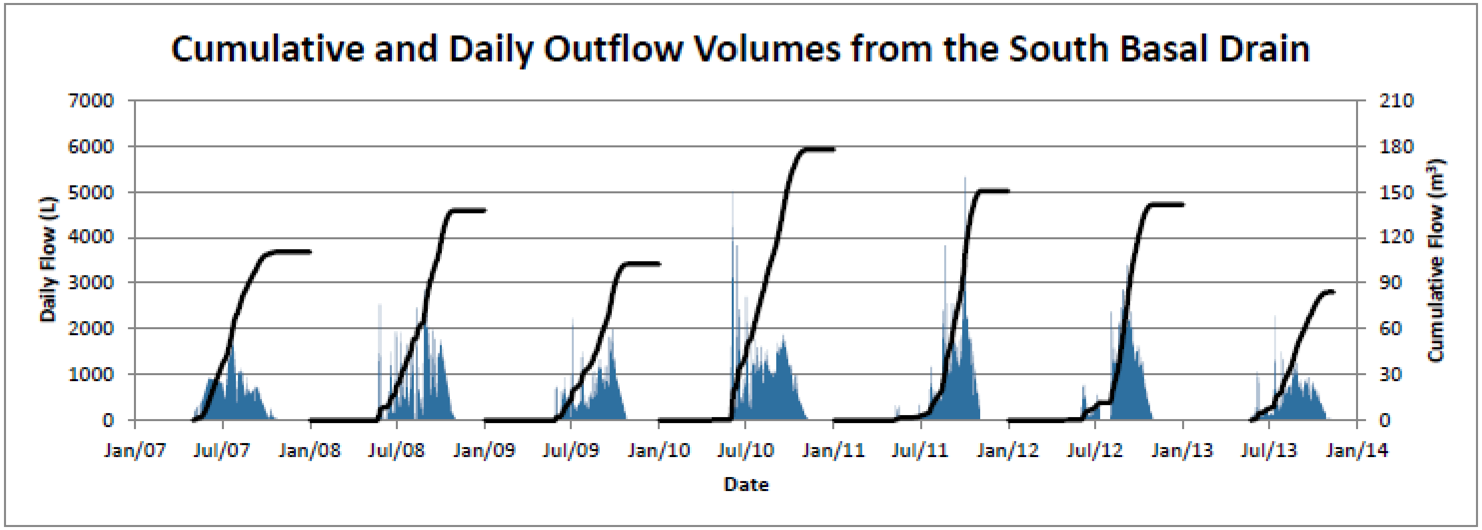


Estimates of Net Infiltration to Crest of Type III pile (Penman-Monteith)

Year	Rainfall (mm)	Estimated Net Infiltration (mm)	Percent Net Infiltration (%)
2006	58 (applied)	51	88* (applied)
2007	153 (61mm applied and 92mm natural)	92	60* (applied and natural)
2008	154	88	57
2009	74	11	15
2010	98	40	41
2011	146	84	58
2012	68	9	13
2013	91	26	29

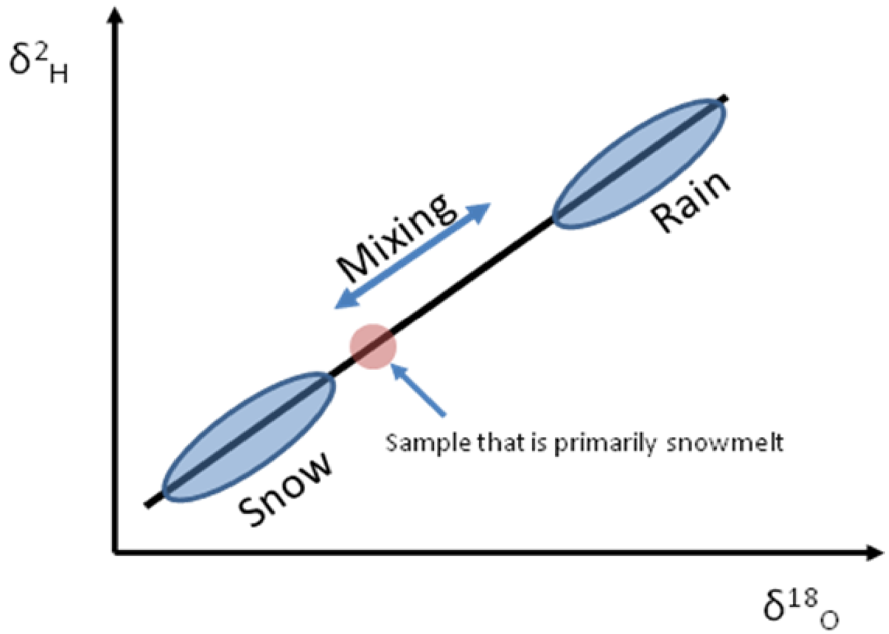
Type III Pile Outflow



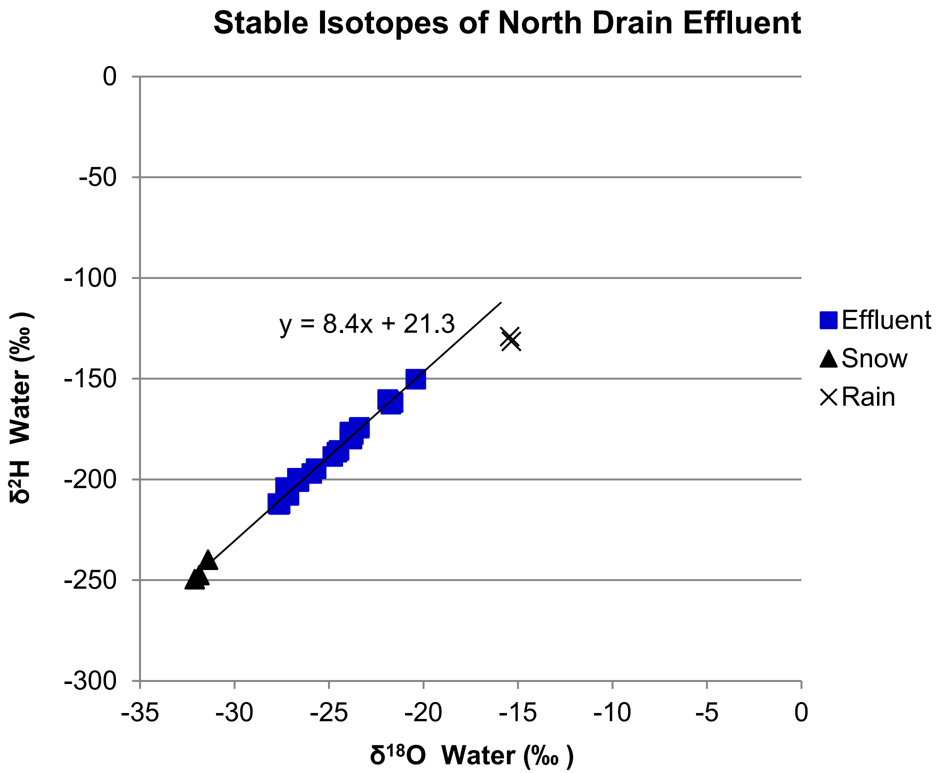


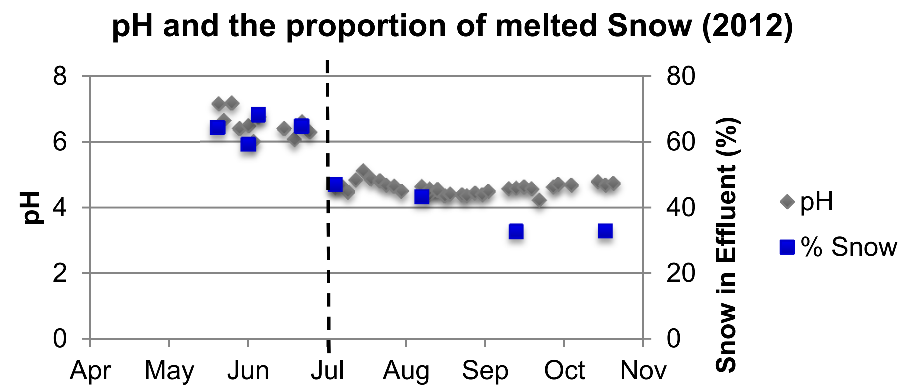
Stable Isotope Analysis

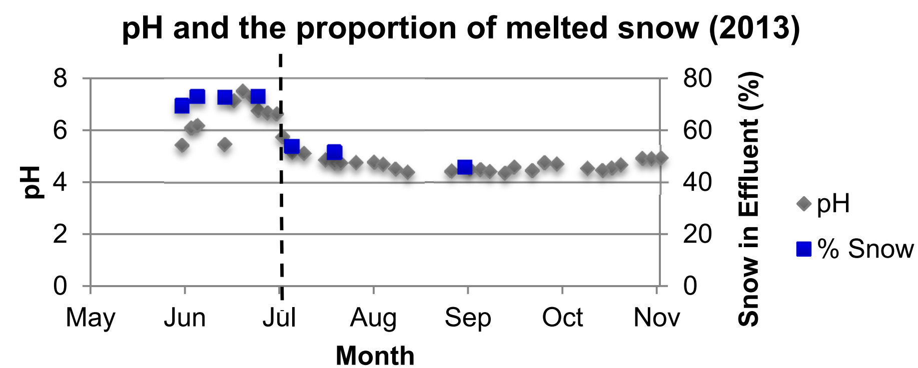
- Goal
  - Determine the contributions of snowmelt and rainfall to recharge through the batters of the type III pile
  - Examine evaporation in the batters of the pile
- Background:
  - Snow and rain have unique isotopic ratios
  - The slope of the line created when plotting stable isotopes gives information about the evaporative history of the sample
- Method
  - Analyze samples of rain, snow, and effluent from the north drain



Stable Isotope Analysis: Results





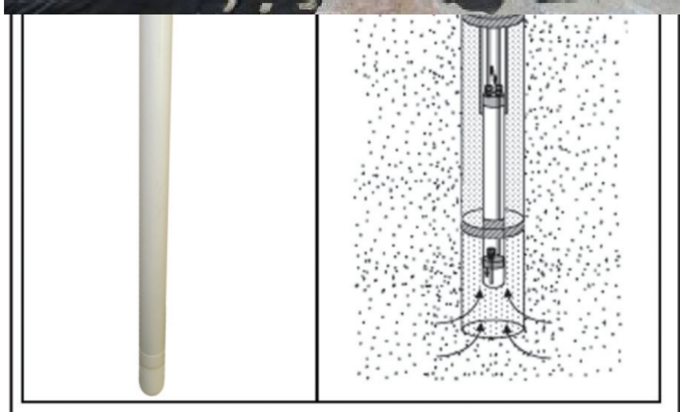


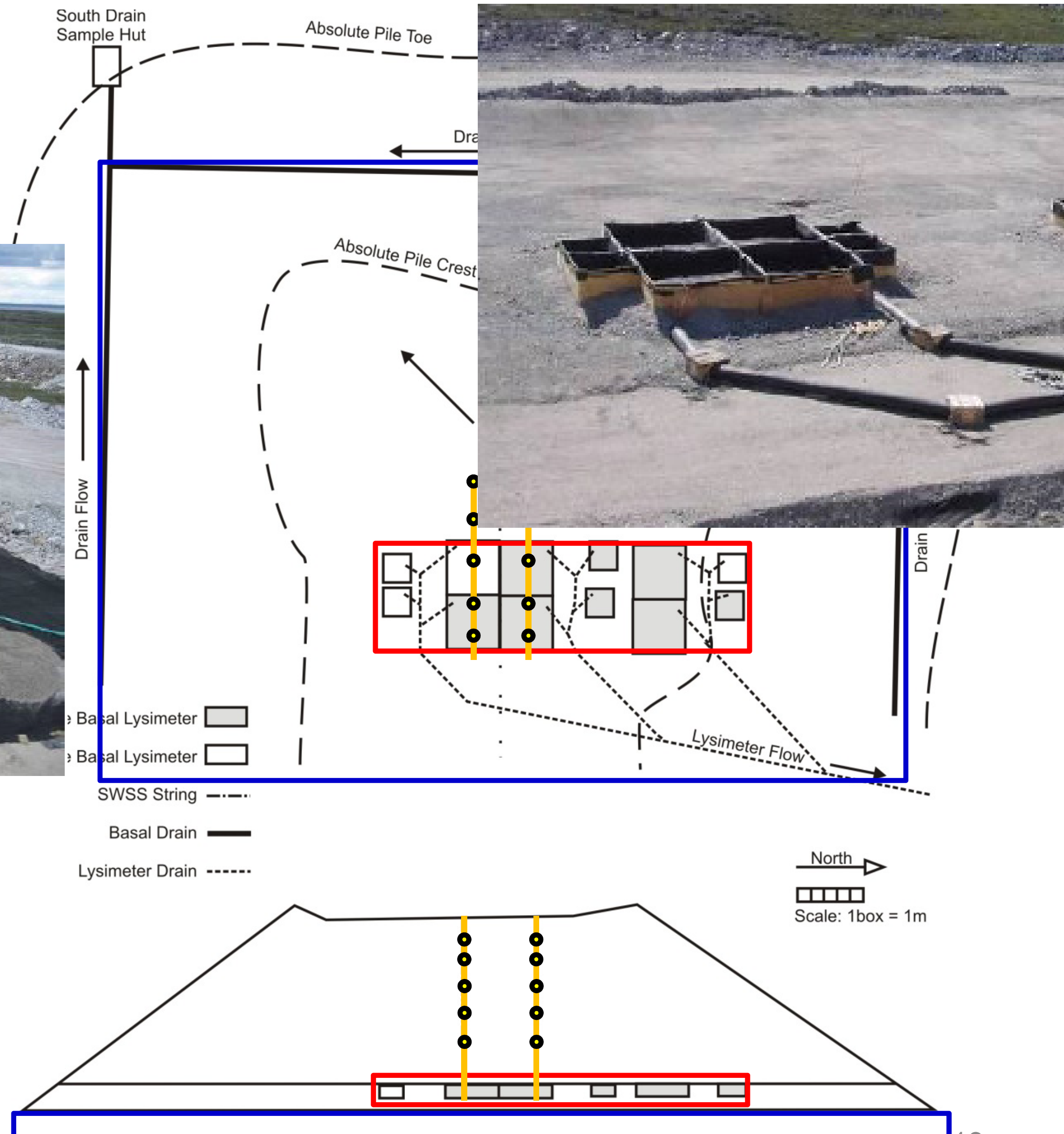
- Slope of the line defined by the effluent ~ 8
- Outflow from May to July heavily influenced by snowmelt
- Good correlation between pH of outflow and the contribution of snowmelt to the outflow

Stable Isotope Analysis: Key Conclusions

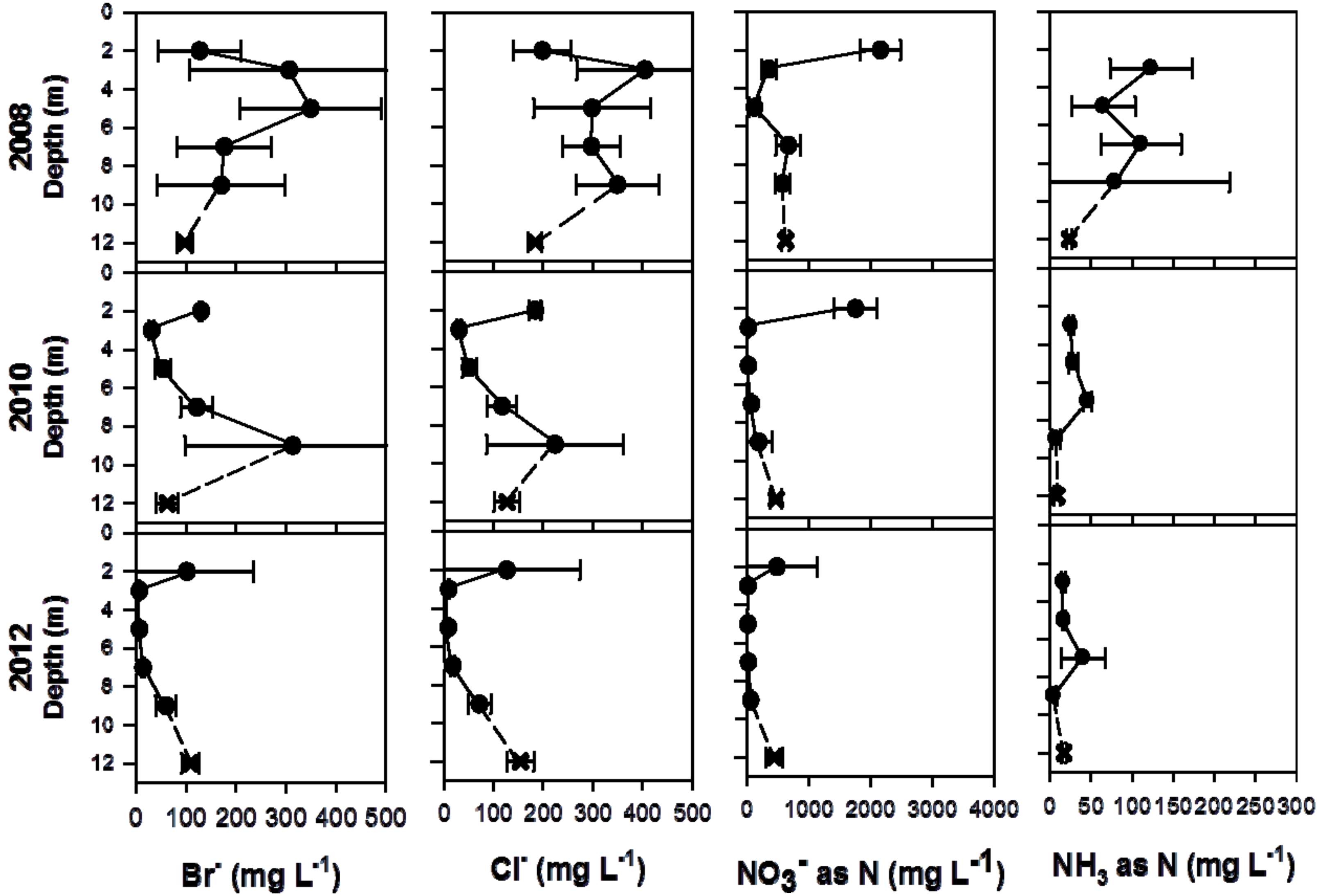
- The circum-neutral outflow observed each spring is a result of snowmelt travelling through preferential pathways to the basal liner
- 40% of the outflow collected by the north drain was derived from the infiltration of snowmelt (2011-2013)
- There is minimal evaporation following the infiltration of water into the north batter of the pile

Flow and Geochemical Data Sources

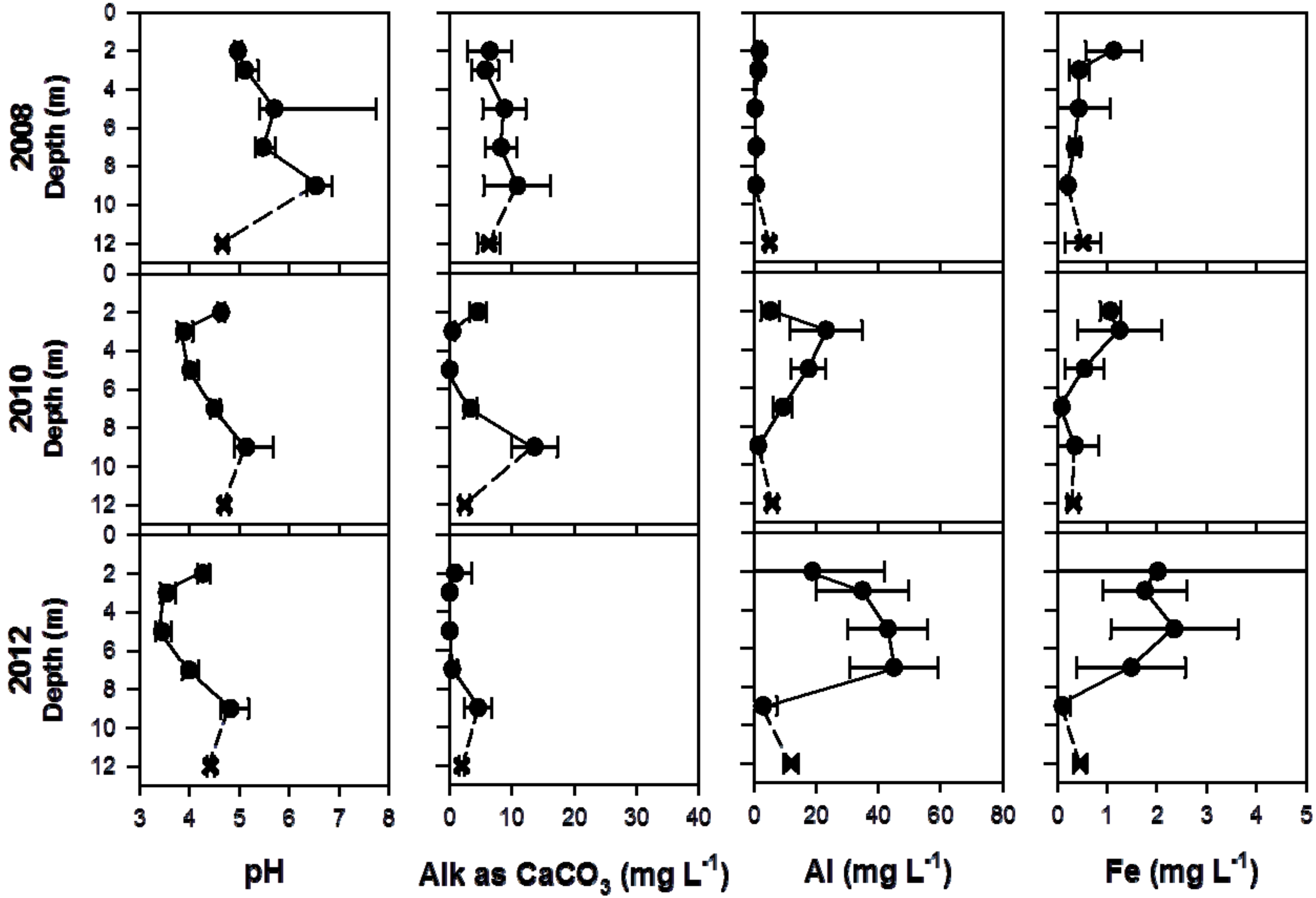




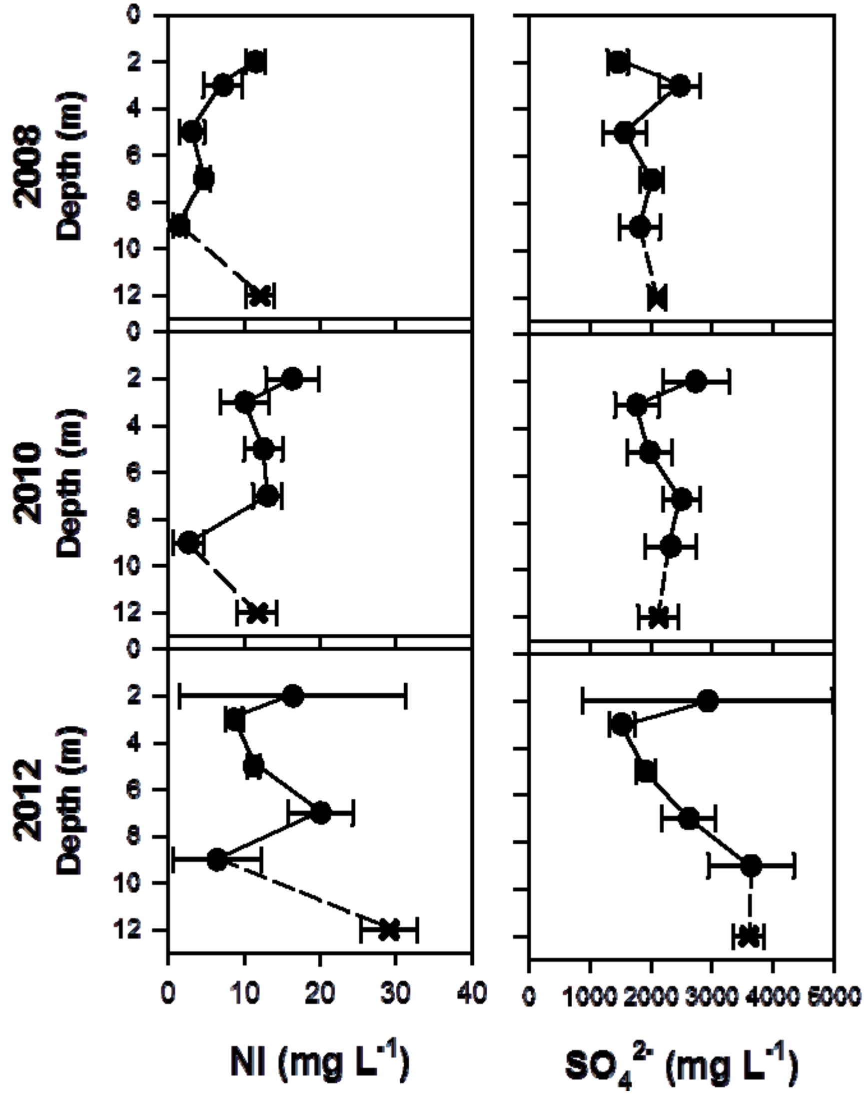
Pile Wet-up and First Flush of Matrix Pore Water



Observations of Progressive Weathering



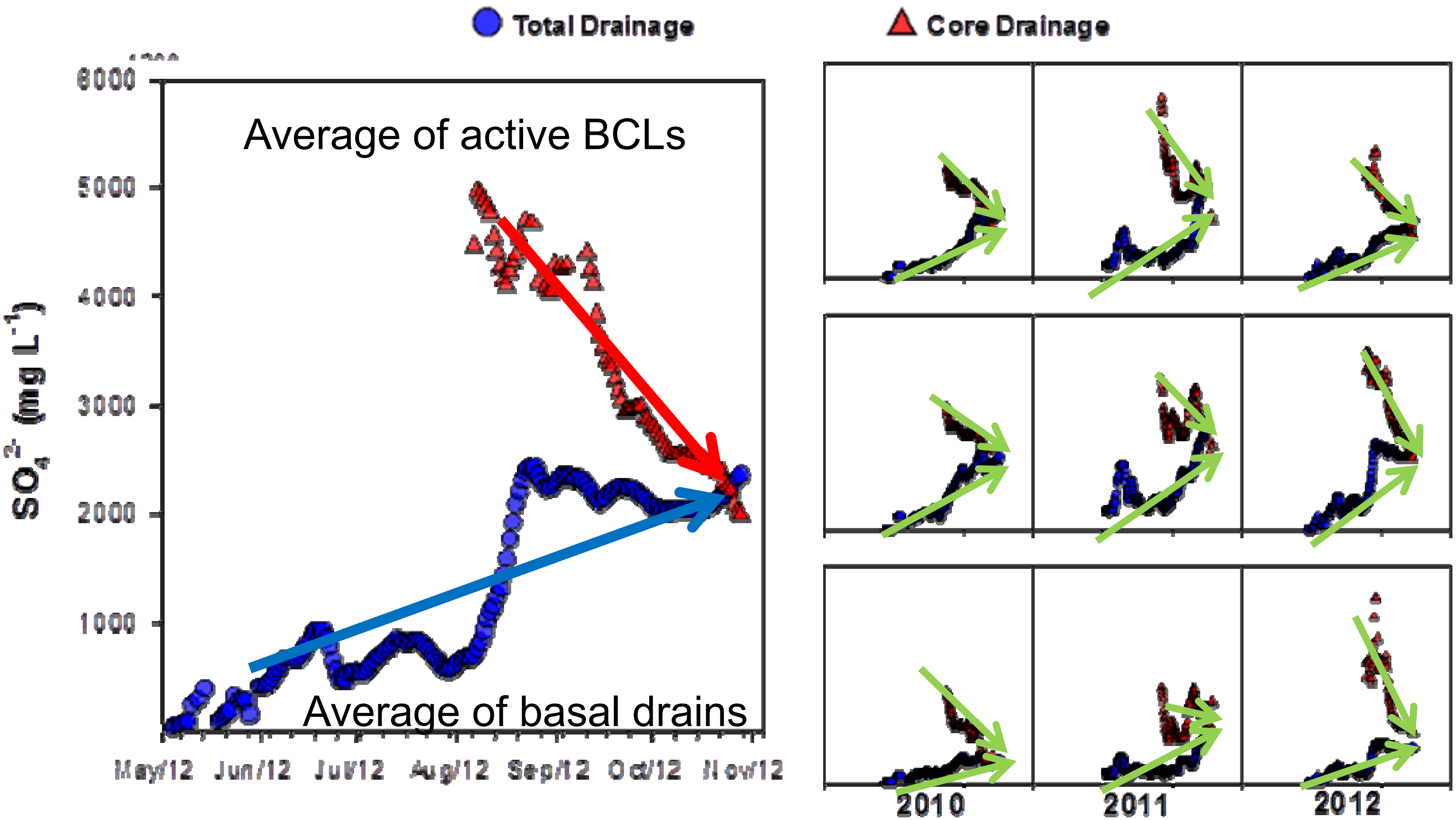
Establishing Internal Geochemical Stability



Geochemical Evolution:

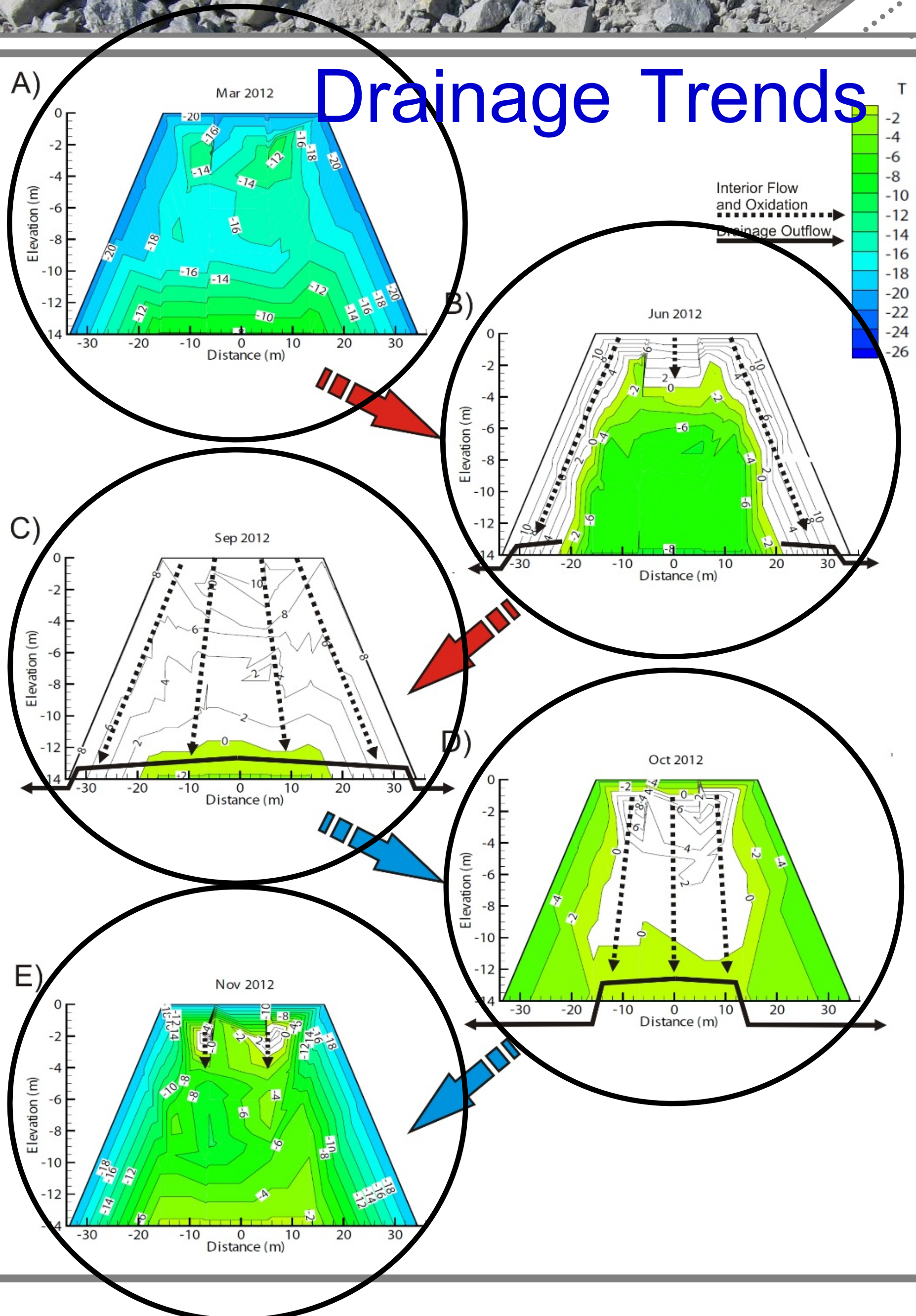
- Wetting front reached the base of the core in 2008 (TDR sensors) confirmed with applied tracers Cl^- and Br^-, as well as blasting residuals NO_3^-, NH_3, and Cl^-
- Declining pH
- Stepwise progression through acid-neutralizing phases
- Increases in SO_4, major cations and trace metals
- Ni is the best indicator of sulfide (pyrrhotite) oxidation – no secondary mineral controls, limited sorption at low pH's in pile

Core Basal Drainage vs. Total Basal Drainage



Continuous flow weighted results - for days without geochemical samples mean values estimated using flow data and bracketing geochemical data

Drainage Trends



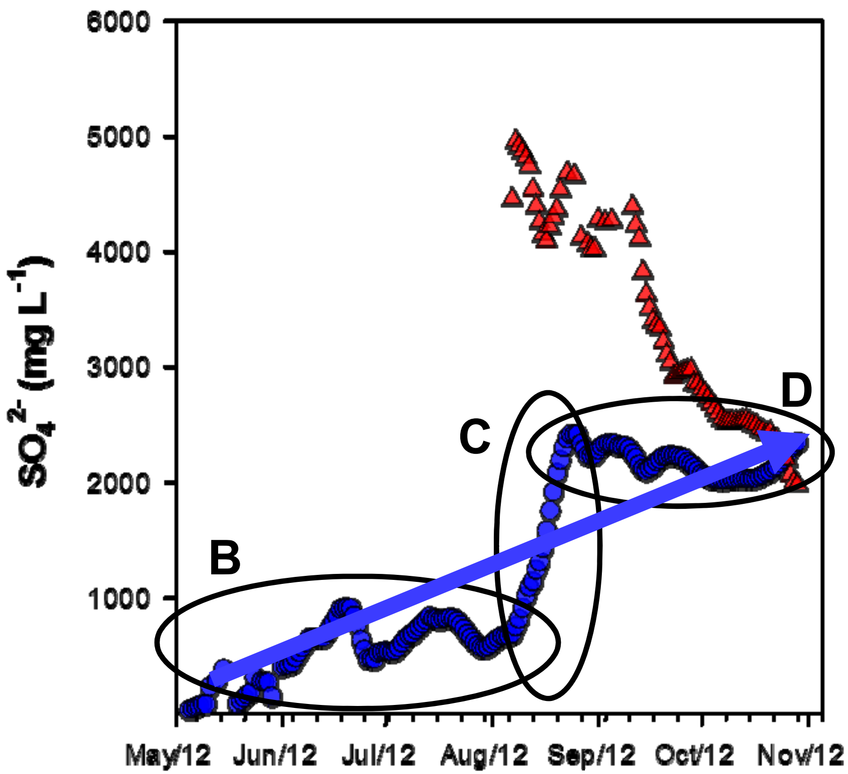
A) Winter – Frozen – No flow

B) Spring – Surface Thaw – Batter flow

C) Late Summer – Full Thaw – Full flow

D) Fall – Batter Freeze – Core flow

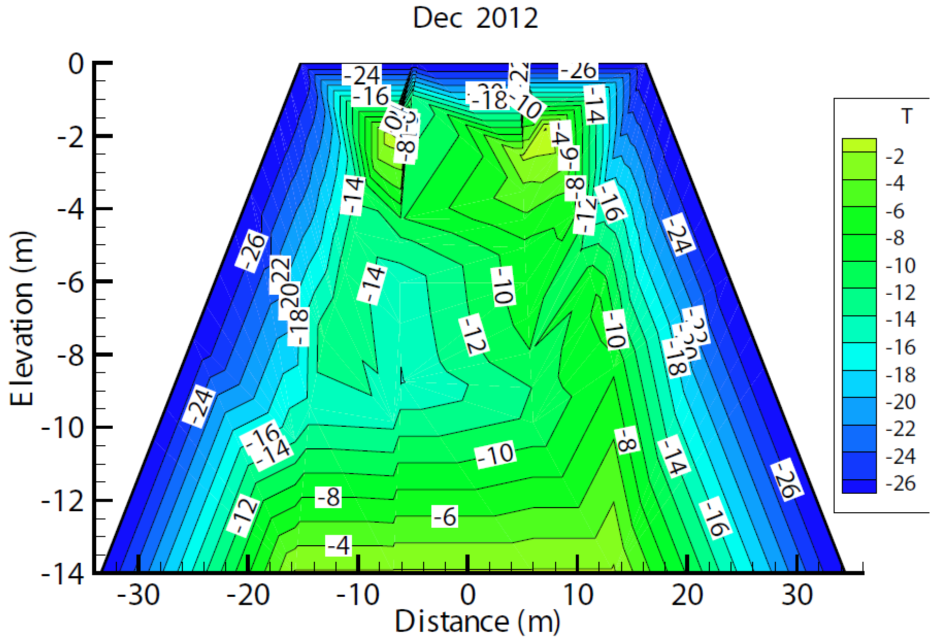
E) Winter – Isolated thawed zones

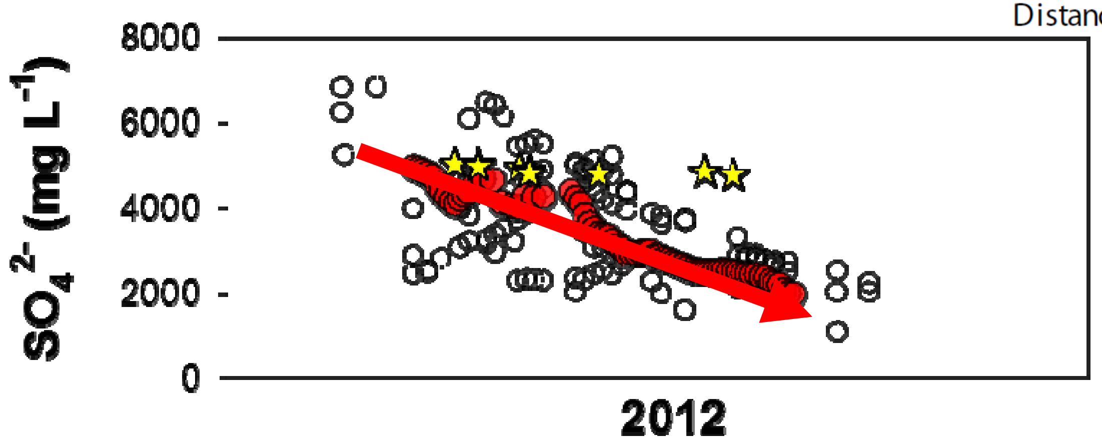


Explaining Core Drainage Trends

Caused by:

1. Residence time / outflow day relationship
2. Sustained winter oxidation, emphasised near the pile base





Humidity Cell Modelling – Scale Up

- Determine relationships between intrinsic rates, temperature and mineral surface area
- Quantify reactions mechanisms

1. Humidity Cells

0.1 m (1 kg)

2. Active Zone Lysimeters

2 m (9,300 kg)

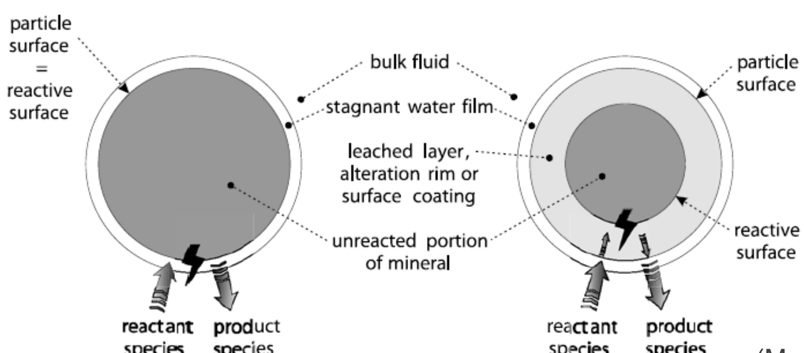
3. Test Piles

15 m (8.2×10^7 kg)

80 m (1.2×10^{11} kg)

Conceptual Model

Sulfide oxidation simulated using shrinking core model.



(Mayer et al., 2002)

Geochemistry

Equilibrium:

- pO_2: 0.21
- pCO_2: 0.000317

Kinetic:

- Pyrrhotite, pentlandite, chalcopyrite, sphalerite, calcite, biotite, muscovite, k-feldspar, albite, and quartz dissolution
- Jarosite, ferrihydrite, gibbsite, and amorphous silica precipitation
- Fe^{2+} and S^0 oxidation

Hydrology

Steady flow:

- Constant flow DI water totaling 500 mL wk^{-1}

n:	0.26
K_{zz}:	2.5×10^{-4} m s^{-1}
Van G. α:	8.8 m^{-1}
Van G. n:	1.7

Conceptual Model

$$Fe^{2+} + 0.25O_{2(aq)} + H^{+} \rightarrow Fe^{3+} + 0.5H_2O$$

Pyrrhotite

$$Fe_{0.852}Ni_{0.004}Co_{0.001}S + 1.714Fe^{3+} \rightarrow 2.566Fe^{2+} + 0.004Ni^{2+} + 0.001Co^{2+} + S^{0}$$

Chalcopyrite

$$CuFeS_2 + 4Fe^{3+} \rightarrow 5Fe^{2+} + Cu^{2+} + 2S^{0}$$

Sphalerite

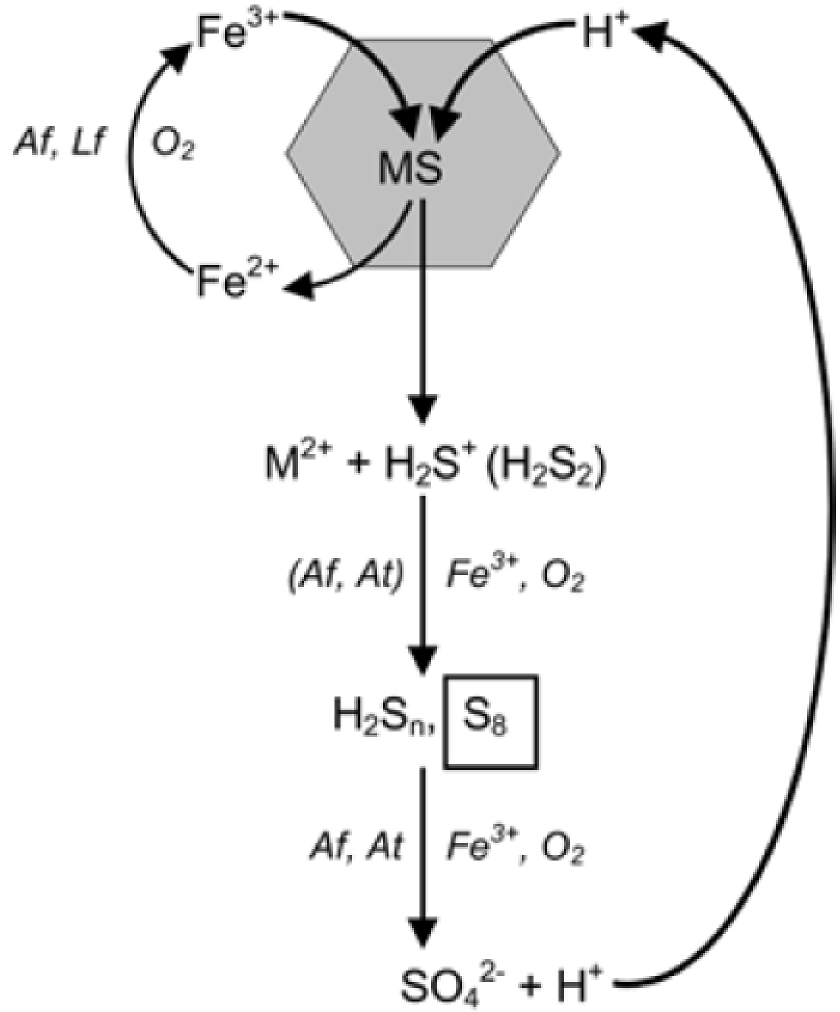
$$ZnS + 2Fe^{3+} \rightarrow 2Fe^{2+} + Zn^{2+} + S^{0}$$

Pentlandite

$$(Fe, Ni, Co)_9S_8 + 18Fe^{3+} \rightarrow 22.5Fe^{2+} + 3.6Ni^{2+} + 0.9Co^{2+} + 8S^{0}$$

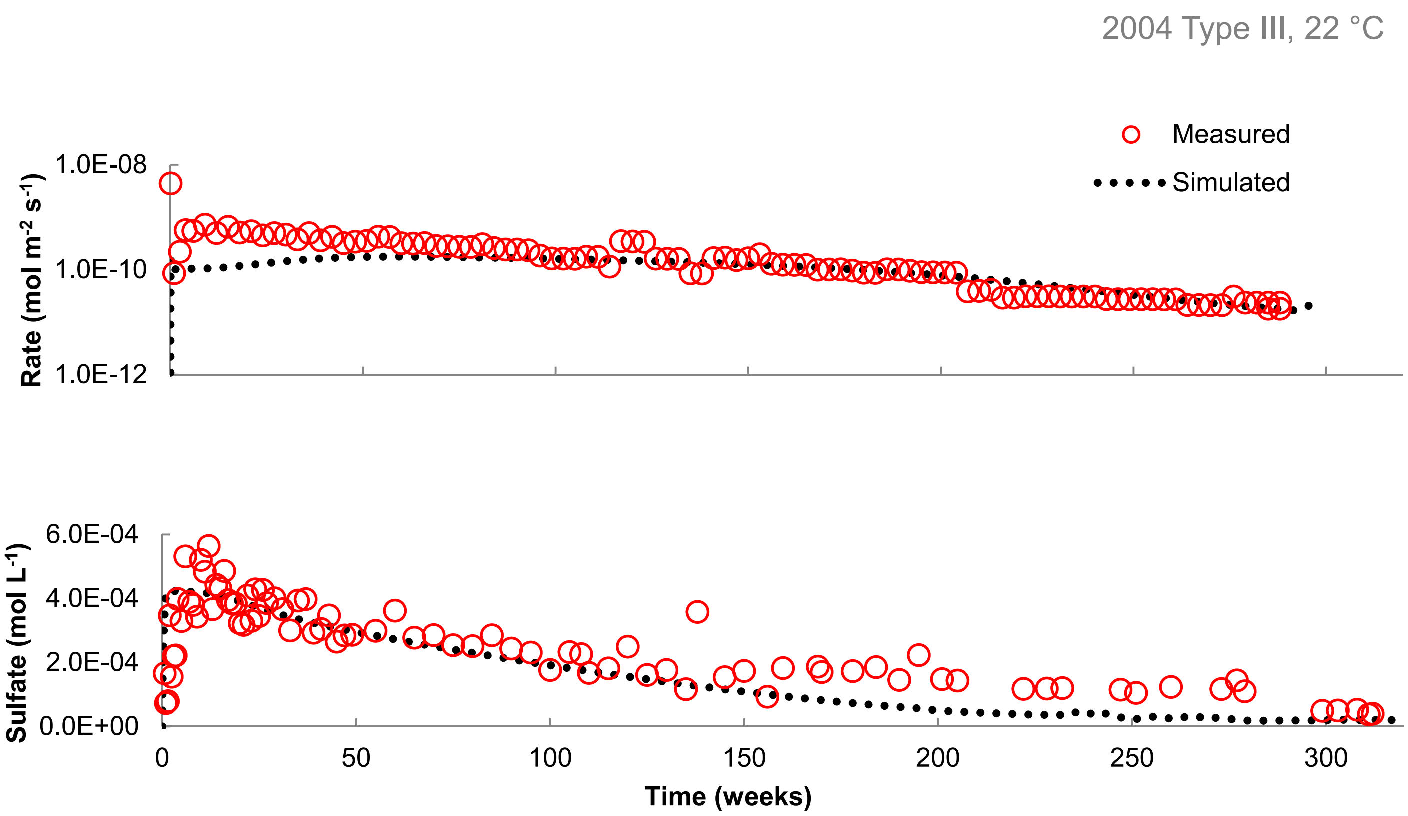
$$S^{0} + 1.5O_{2(aq)} + H_2O \rightarrow SO_4^{2-} + 2H^{+}$$

polysulfide mechanism of sulfide mineral oxidation



Rohwerder et al., 2003

Preliminary Geochemical Solution



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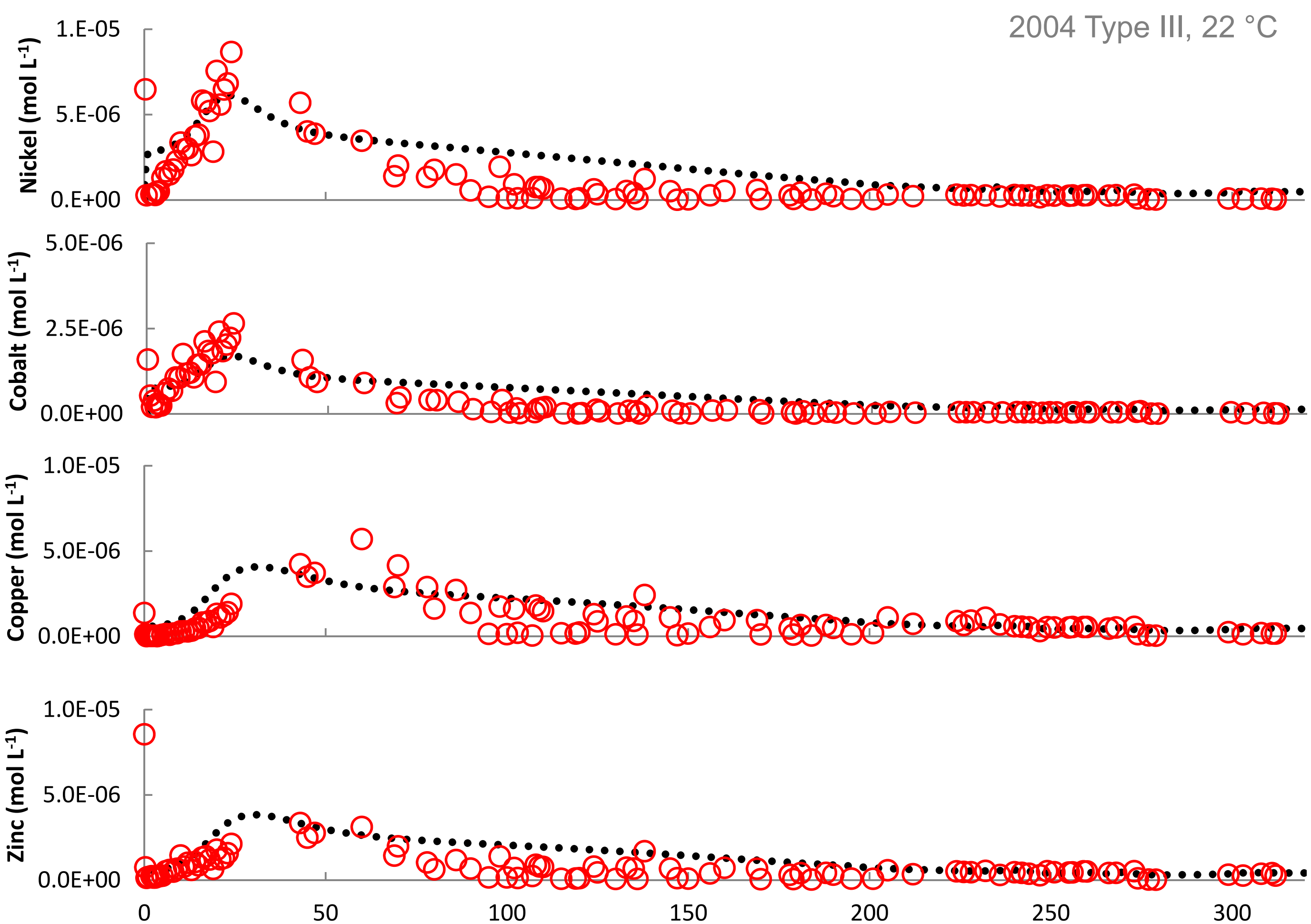

Journal Publications

- Amos, R.T., Blowes, D.W., Bailey, B.L., Sego, D.C., Smith, L., Ritchie, A.I.M. (In press) Waste-rock hydrogeology and geochemistry. Applied Geochemistry.
- Langman, J.B., Moore, M.L., Ptacek, C.J., Smith, L., Sego, D., Blowes, D.W. (2014) Diavik waste rock project: evolution of mineral weathering, element release, and acid generation and neutralization during a five-year humidity cell experiment. *Minerals*, 4, 257-278.
- Matthies, R., Sinclair, S.A., Blowes, D.W. (2014) The zinc stable isotope signature of waste rock drainage in the Canadian permafrost region. *Applied Geochemistry*, 48, 53-57.
- **Applied Geochemistry (2013)**
  - Bailey, B.L., Smith, L.J.D., Blowes, D.W., Ptacek, C.J., Smith, L., Sego, D.C. (2013) Diavik waste rock project: Persistence of contaminants from blasting agents in waste rock effluent. Applied Geochemistry 36, 256-270.
  - Chi, X., Amos, R.T., Stastna, M., Blowes, D.W., Sego, D.C., Smith, L. (2013)). Diavik waste rock project: Implications of wind-induced gas transport in a waste rock pile. Applied Geochemistry 36 , 246-255.
  - Neuner, M., Smith, L., Blowes, D.W., Sego, D.C., Smith, L.J.D., Fretz, N., Gupton, M. (2013) Diavik waste rock project: Water flow through mine waste rock in a permafrost terrain. Applied Geochemistry 36, 222-233.
  - Pham, N.H., Sego, D.C., Arenson, L.U., Blowes, D.W., Amos, R.T., Smith, L. (2013). The Diavik waste rock project: Measurement of the thermal regime of a waste rock pile in a permafrost environment. Applied Geochemistry 36, 234-245.
  - Smith, L.J.D., Moncur, M.C., Neuner, M., Gupton, M., Blowes, D.W., Smith, L., Sego, D.C. (2013a) Diavik waste rock project: Design, construction, and instrumentation of fieldscale experimental waste-rock piles. Applied Geochemistry 36, 187-199.
  - Smith, L.J.D., Blowes, D.W., Jambor, J.L., Smith, L., Sego, D.C., Neuner, M. (2013b) The Diavik Waste Rock Project: Particle size distribution and sulfur characteristics of lowsulfide waste rock. Applied Geochemistry 36, 200-209.
  - Smith, L.J.D., Bailey, B.L., Blowes, D.W., Jambor, J.L., Smith, L., Sego, D.C. (2013c) Diavik waste rock project: Initial geochemical response from a low sulfide waste rock pile. Applied Geochemistry 36, 210-221.
- Amos et al., (2009). Measurement of wind induced pressure gradients in a waste rock pile. *Vadose Zone Journal, 8, 953-962. doi:10.2136/vzj2009.0002.*

Questions?