Diavik Waste Rock Project

Northern Aspects and Scaling Predictions

Richard T. Amos
Brenda L. Bailey
Nam Pham
Nathan Fretz
Stacey Hannam
David W. Blowes
David C. Sego
Leslie Smith

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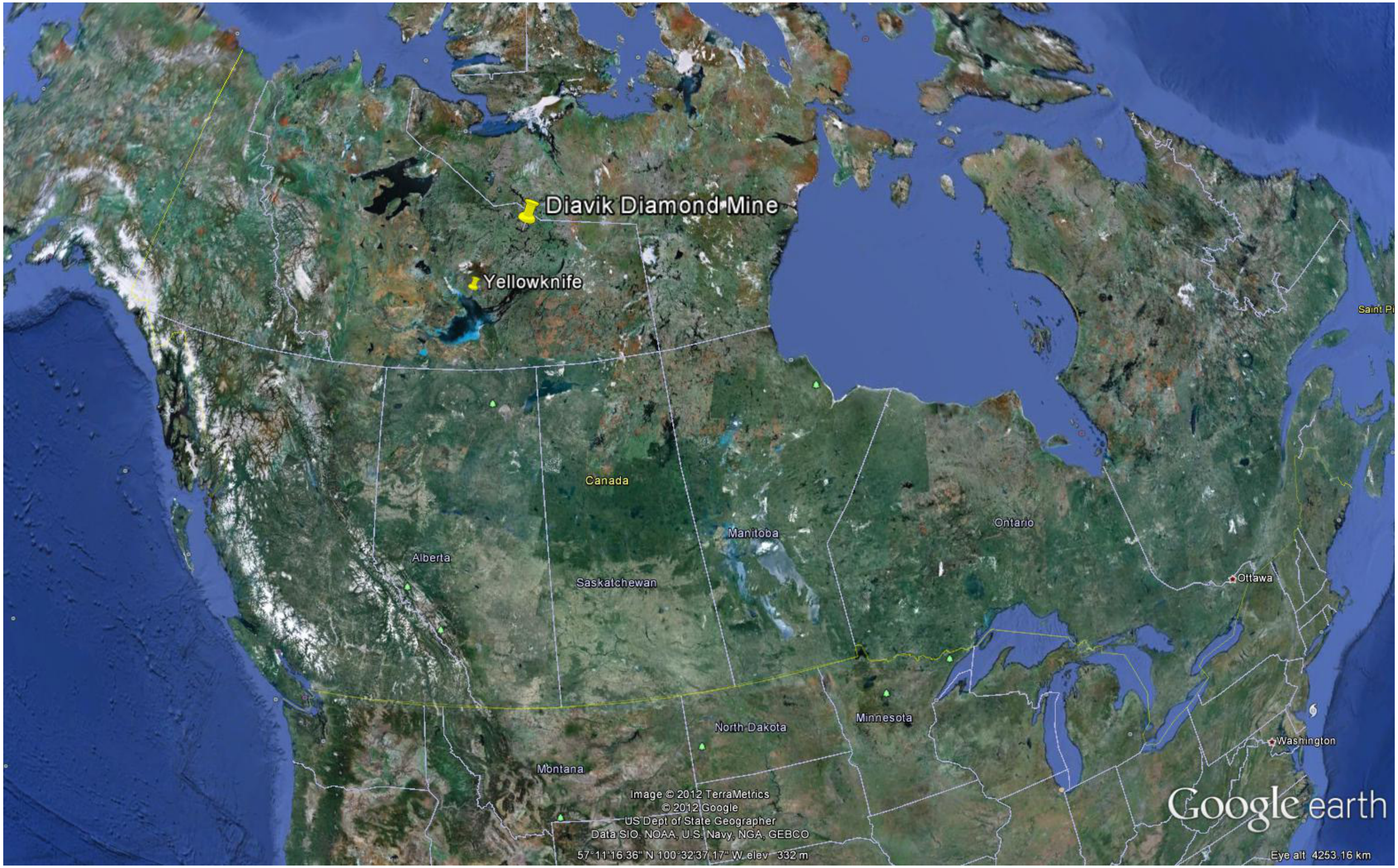
Site Location



Introduction – Site location

Research Goals – Diavik Waste Rock Project

- Understand the geochemical, hydrological, and thermal conditions controlling the generation of acidic leachate from waste rock stockpiles in a permafrost environment
- Determine the value of small-scale laboratory tests for predicting if and when low quality drainage may be released from a stockpile.

Introduction – Test piles background

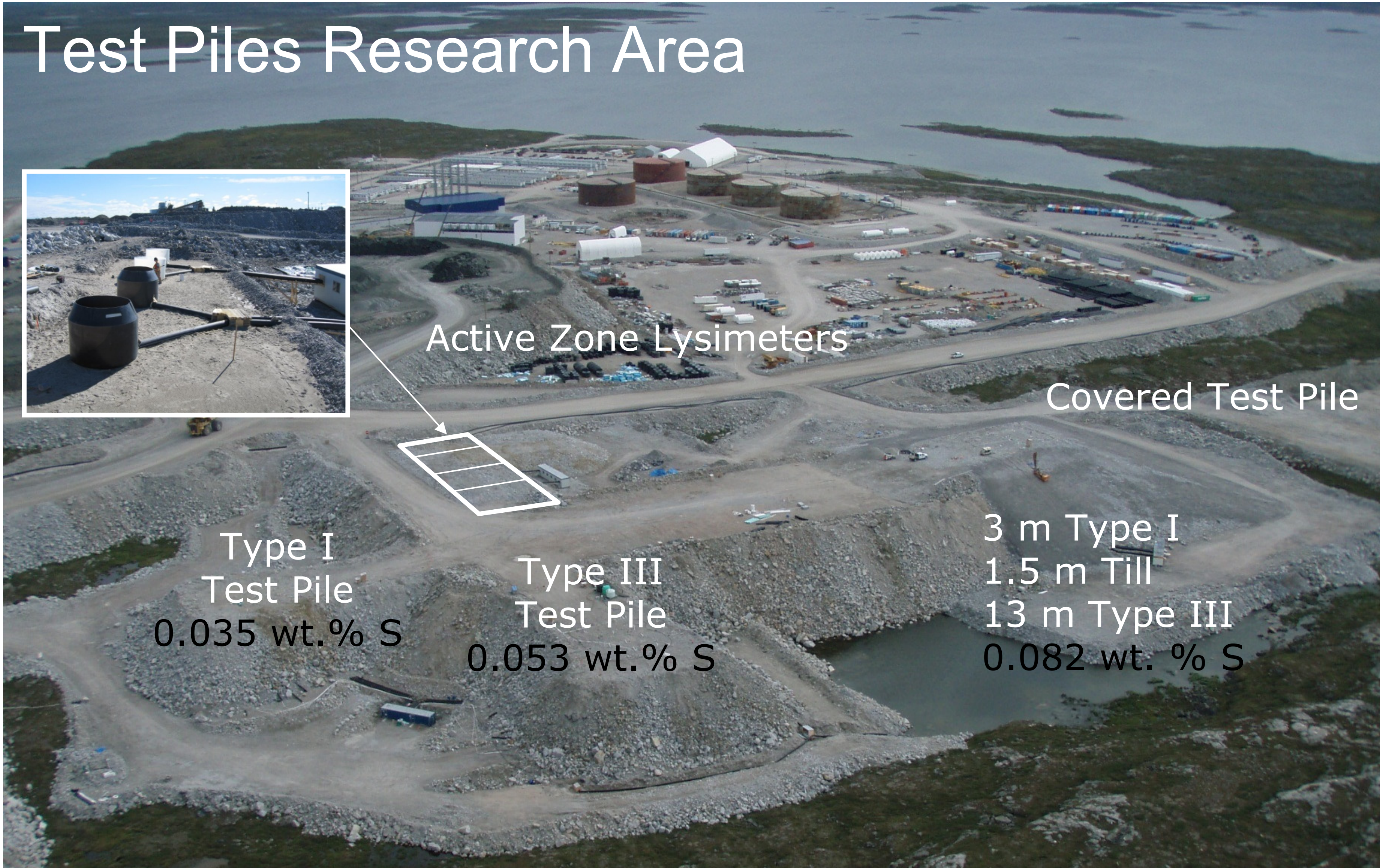
- Waste rock type/management

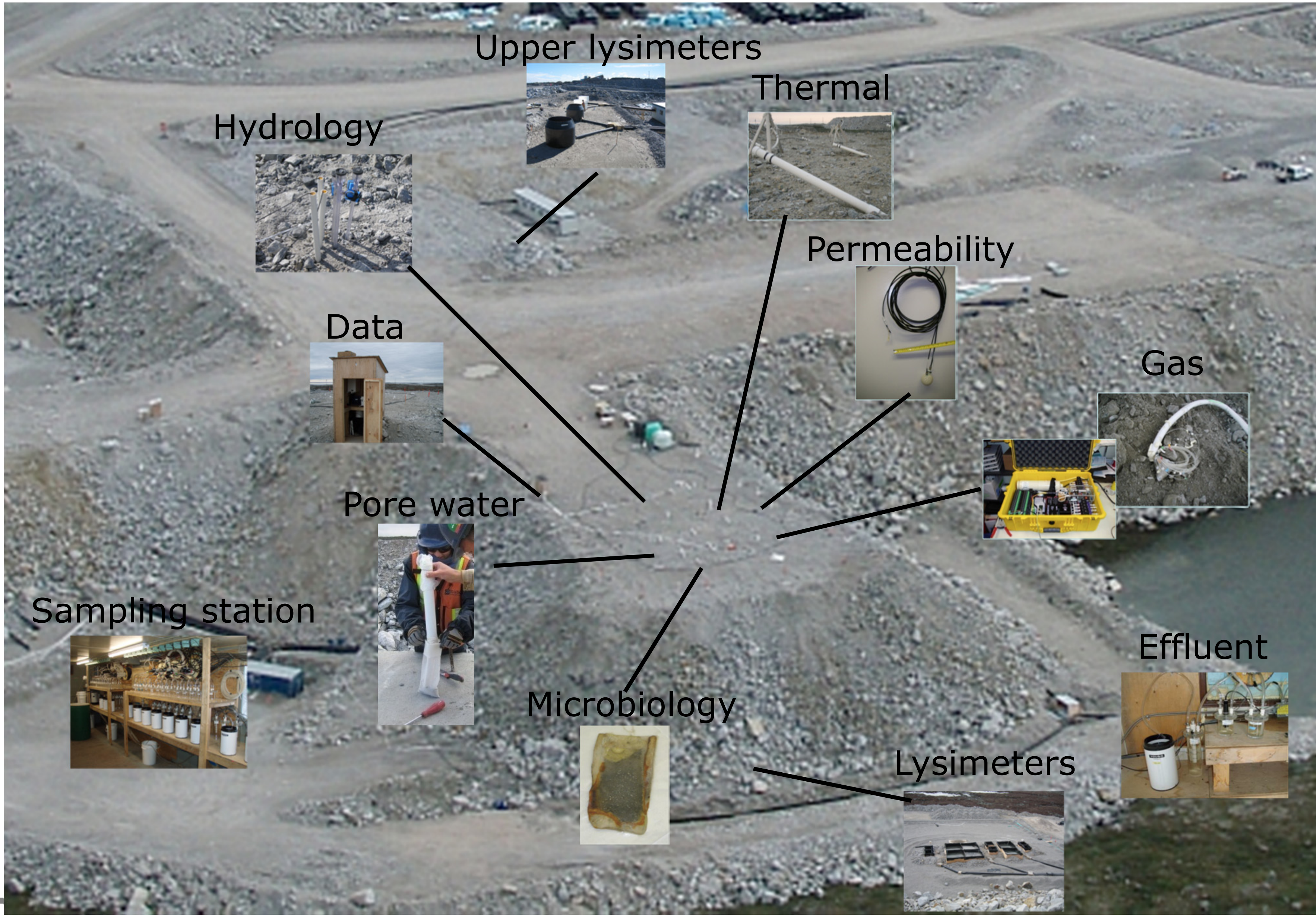
Type I	< 0.04 wt. % S	Predominantly granites
Type II	0.04 – 0.08 wt. % S	Predominantly granites with small amount of biotite schist
Type III	>0.08 wt. % S	Predominantly granites with greater amount of biotite schist

Research Facilities

- Laboratory humidity cell experiments
  - 18 Cold room
  - 18 Room Temperature
- 2 m-scale active zone experiments
  - 2 Type I (low sulfide)
  - 2 Type III (higher sulfide)
- Test-scale waste rock piles
  - Type I (low sulfide)
  - Type III (higher sulfide)
  - Covered (Type III core with till and Type I cover)
- Instrumented full-scale waste rock dump
  - 4 x 40 m vertical drill holes
  - 1 x 80 m vertical drill hole
  - Horizontal instrument lines

Test Piles Research Area




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

Full-scale Instrumentation

- 3 drill holes
  - 32, 31 and 40 m deep
- 80 m drill hole
- 40 m drill hole
- Horizontal Installation
  - 120 m and 280 m

- Thermistors, Gas sampling lines, Thermal conductivity, Microbiology , SWSS , Permeability, ECH_2O probes,
- Cuttings collected
  - Mineralogy, Sulfur and Carbon analysis

Journal Publications

- **Applied Geochemistry (2012)**
  1. Bailey et al., Diavik Waste Rock Project: Persistence of contaminants from blasting agents in waste rock effluent.
  2. Chi et al., The Diavik Waste Rock Project: Implications of wind-induced gas transport.
  3. Neuner et al., The Diavik Waste Rock Project: Water flow though mine waste rock in a permafrost terrain.
  4. Smith et al., The Diavik Waste Rock Project: Design, construction, and instrumentation of field-scale experimental waste-rock piles.
  5. Smith et al., The Diavik Waste Rock Project: Initial geochemical response from a low sulfide waste rock pile.
- 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.*

Conference Presentations and Proceedings

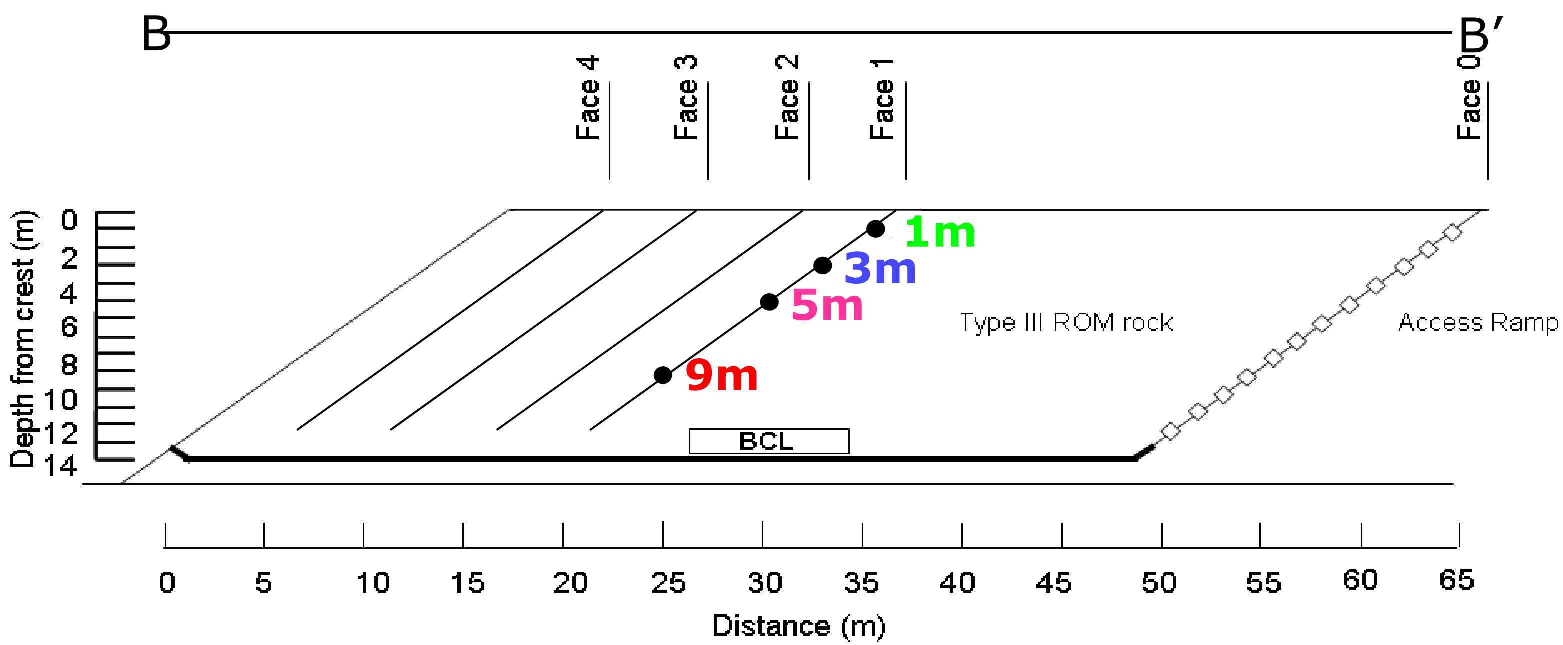
- **Tailing and Mine Waste (November 6-9, 2011, Vancouver)**
  - Bailey et al., (2011). Diavik Waste Rock Project: Blasting Residuals In Waste Rock Piles.
  - Fretz et al., Diavik Waste Rock Project: Unsaturated Water Flow.
  - Pham et al., Diavik Waste Rock Project: Thermal transport in a covered waste rock test pile.
  - Smith et al., Diavik Waste Rock Project: Characterization of Particle Size, Sulfur Content and Acid Generating Potential.
- **2012 ICARD (May 20-26, 2012, Ottawa, ON, Canada.)**
  - Amos et al, , Diavik Waste Rock Project: Wind-Induced Gas Transport.
  - Bailey et al., Diavik Waste Rock Project: Geochemistry of low sulfide content large-scale waste rock piles.
  - Bailey et al., Diavik Waste Rock Project: Microbiological succession in waste rock piles.
  - Fretz et al., Diavik Waste Rock Project: Preliminary Estimates of Infiltration.
  - Hannam et al., Diavik Waste Rock Project: Synchrotron-based investigation of sulfide mineral weathering.
  - Pham et al., Diavik Waste Rock Project: Heat transport and the effects of climate change in a waste rock pile located in a continuous permafrost region of Northern Canada.
  - Smith et al., Diavik Waste Rock Project: Objectives, implications and current conclusions.
  - Stanton et al., Diavik Waste Rock Project: Laboratory studies.

Research Highlights

Hydrology

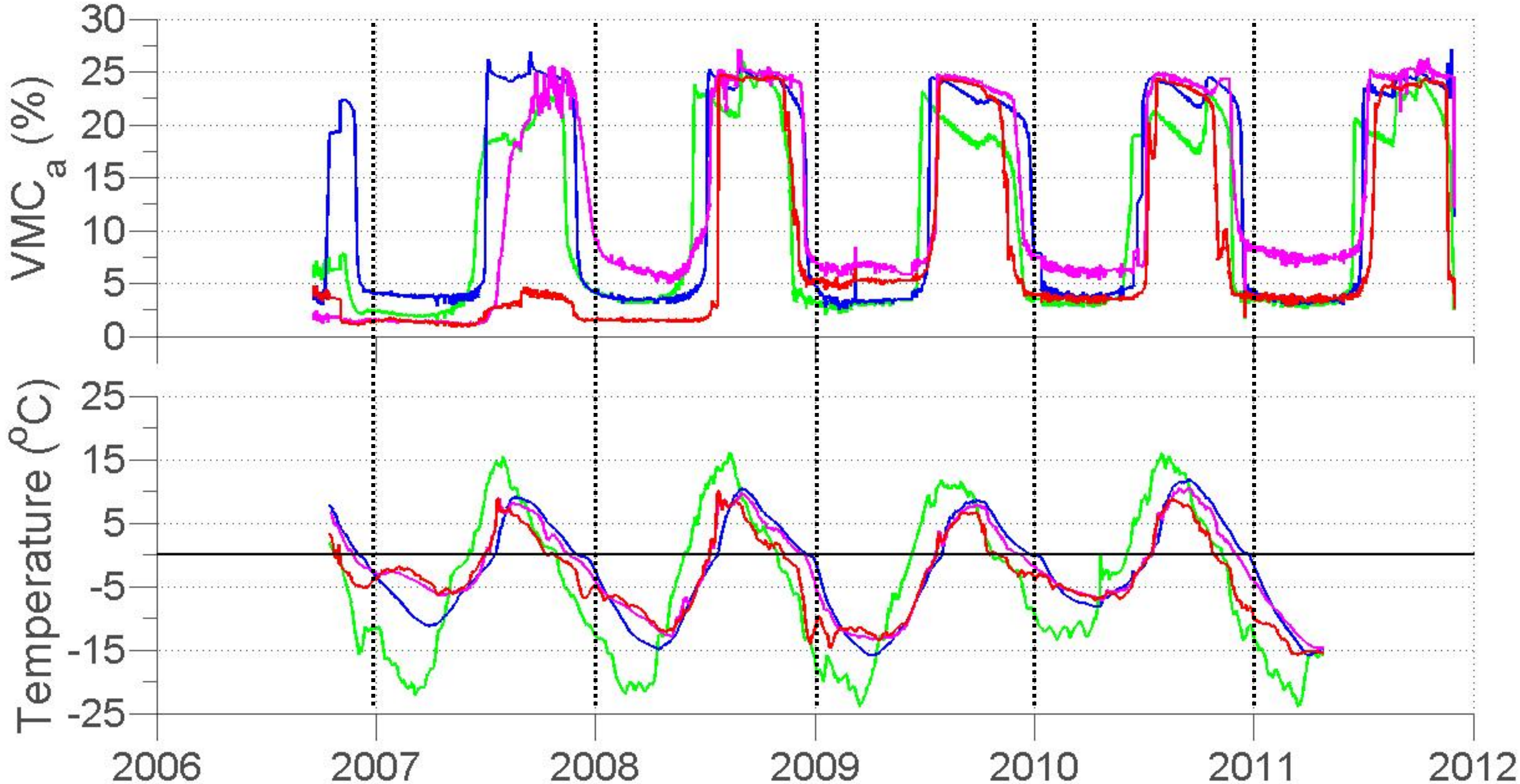
TDR Locations – Type III Test Pile

- TDR sensors installed below crown of test pile



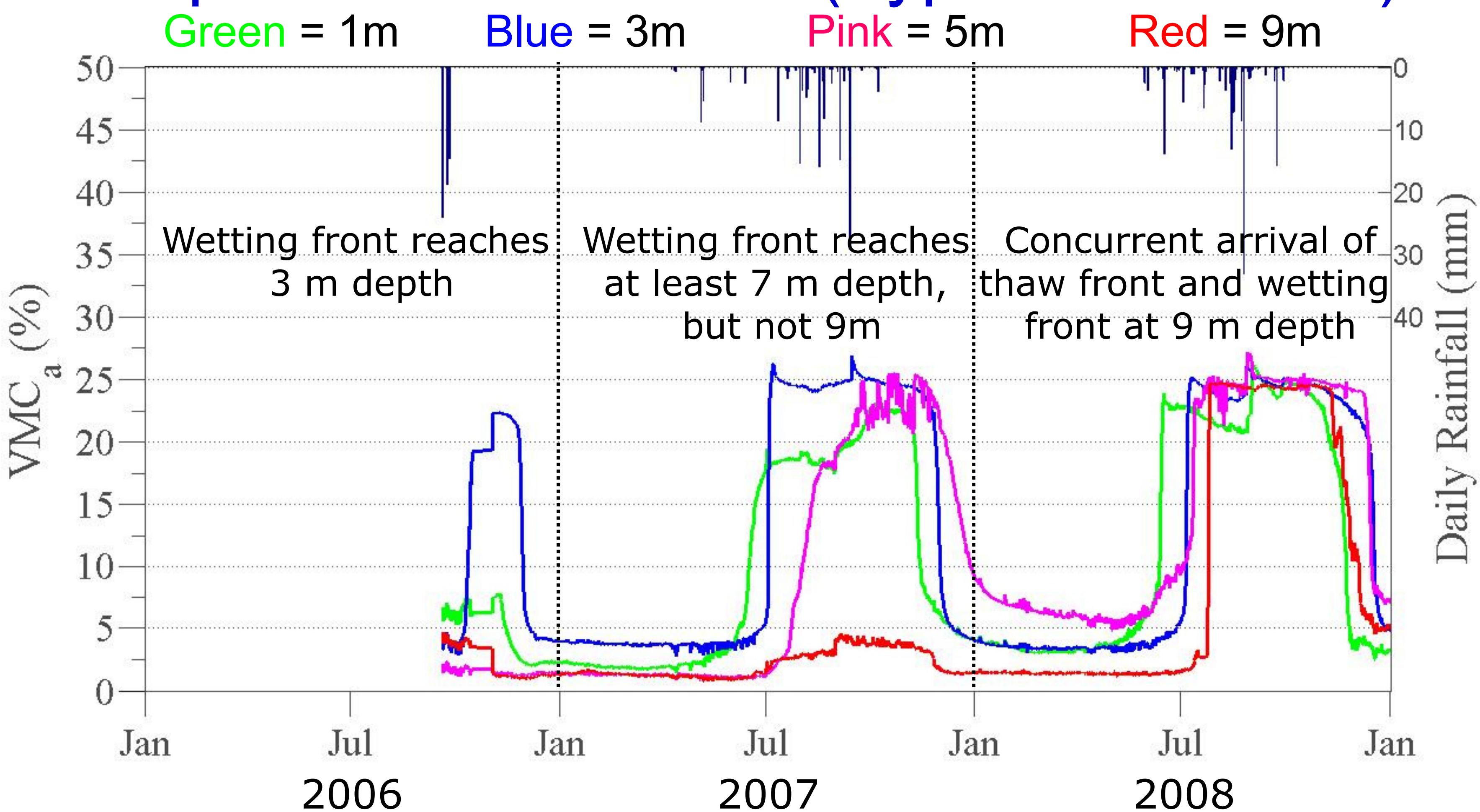
Freeze-Thaw Cycle (Type III Test Pile)

Green = 1m Blue = 3m Pink = 5m Red = 9m



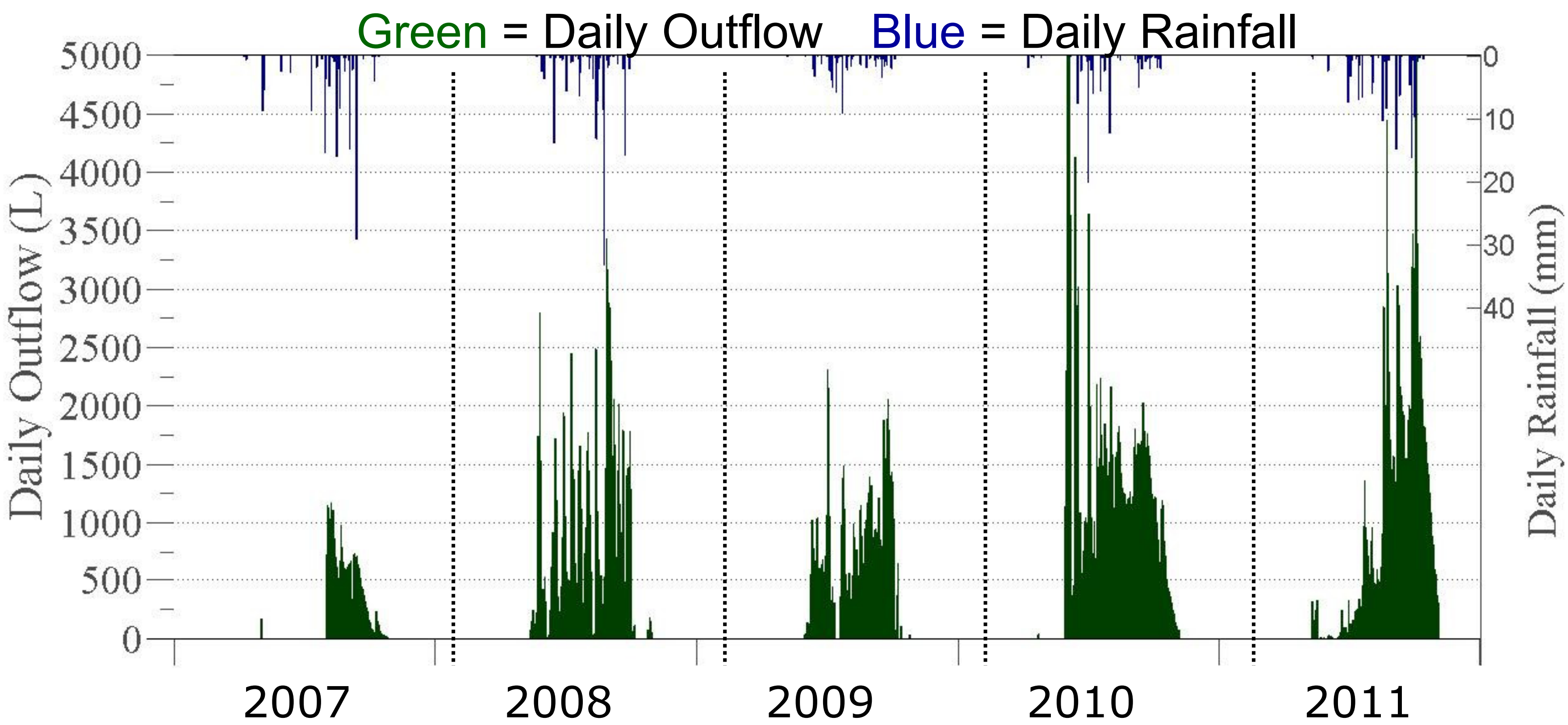
- Ambient air temperature restricts infiltration and water movement in the test pile.
- The portion of the test pile that contributes to outflow changes with the generation of the active-zone.

Wet-Up of Matrix Fraction (Type III Test Pile)



Basal collection lysimeters at the base of the test pile recorded outflow starting in September of 2008.

Annual Outflow Response (Type III Test Pile)



	2007	2008	2009	2010	2011
Total Rainfall:	92 mm	154 mm	74 mm	98 mm	146 mm
% of Avg:	55%	92%	44%	58%	87%
Total Outflow:	110 m^3	150 m^3	117 m^3	213m^3	176 m^3

Annual Outflow Response (Test Pile)

- Variations in the timing and magnitude of outflow over multiple years are a function of:
  - Timing of active-zone generation
  - Snow accumulation and melt
  - Timing and magnitude of rainfall events
  - Antecedent moisture contents and wetting front locations held in storage over the previous winter

- TDR, basal collection lysimeter, and basal drain response indicate that, in terms of outflow volumes, the test piles are batter dominated systems.
  - 100%, 84%, 94%, 97%, and 72% of total outflow in 2007, 2008, 2009, 2010, and 2011, respectively

Methods for estimating net infiltration

1. Water balance at the AZLs to back-out net infiltration

Net Infiltration = Rainfall - Evaporation
= **AZL Annual Outflow**

2. FAO-Model to estimate evaporation

FAO Penman-Monteith formulation → ET_o = reference evapotranspiration

$$= \frac{0.408\Delta(R_n - G) + \gamma(37/(T_{hr} + 273))u_2(e^o(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Coefficient to determine actual evaporation

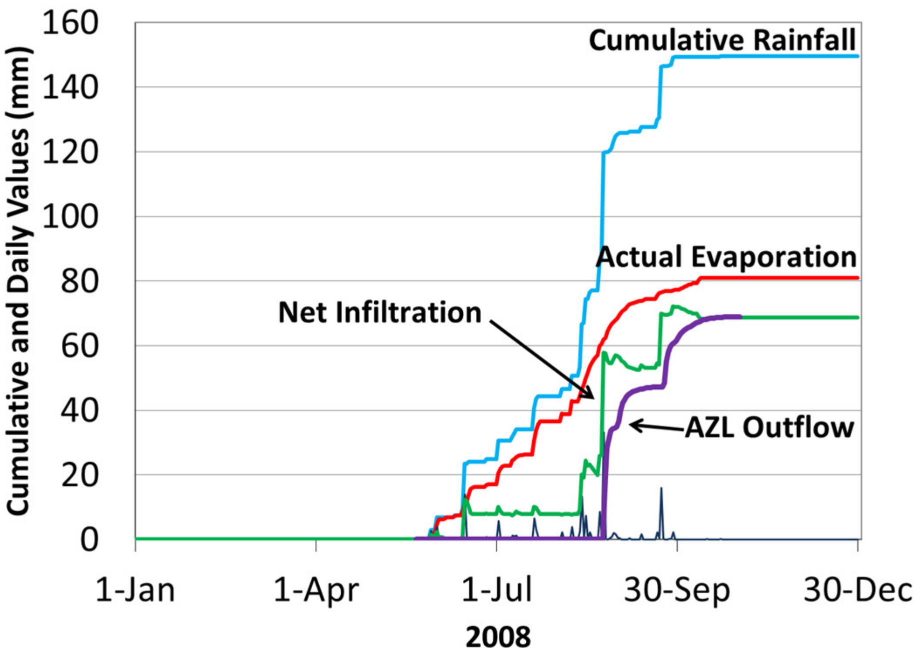
$E = K_e ET_o K_f$

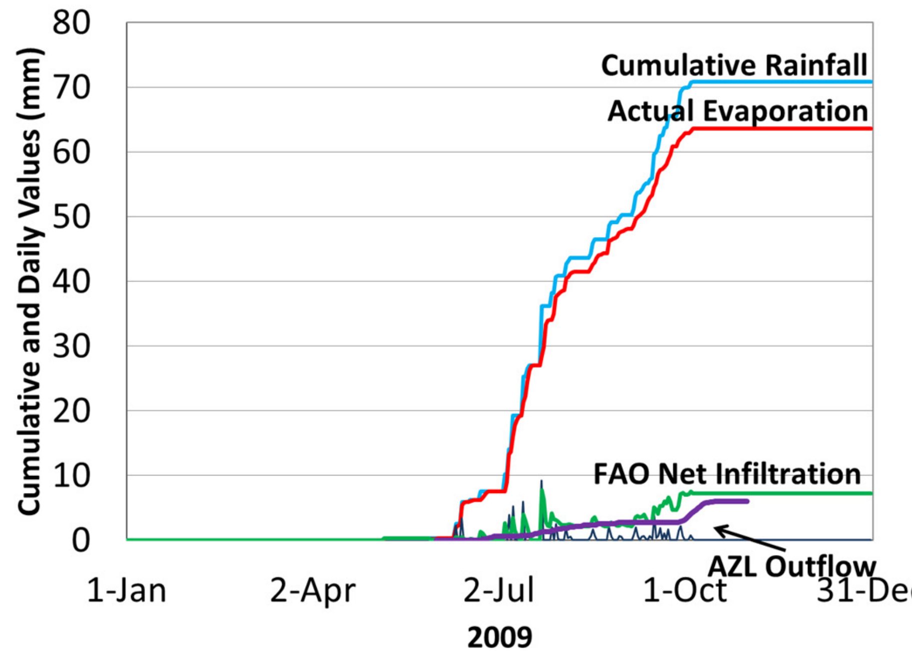
E = actual evaporation

K_e = soil evap. coefficient
K_f = frozen soil coefficient

Net infiltration = Rainfall – Actual Evaporation

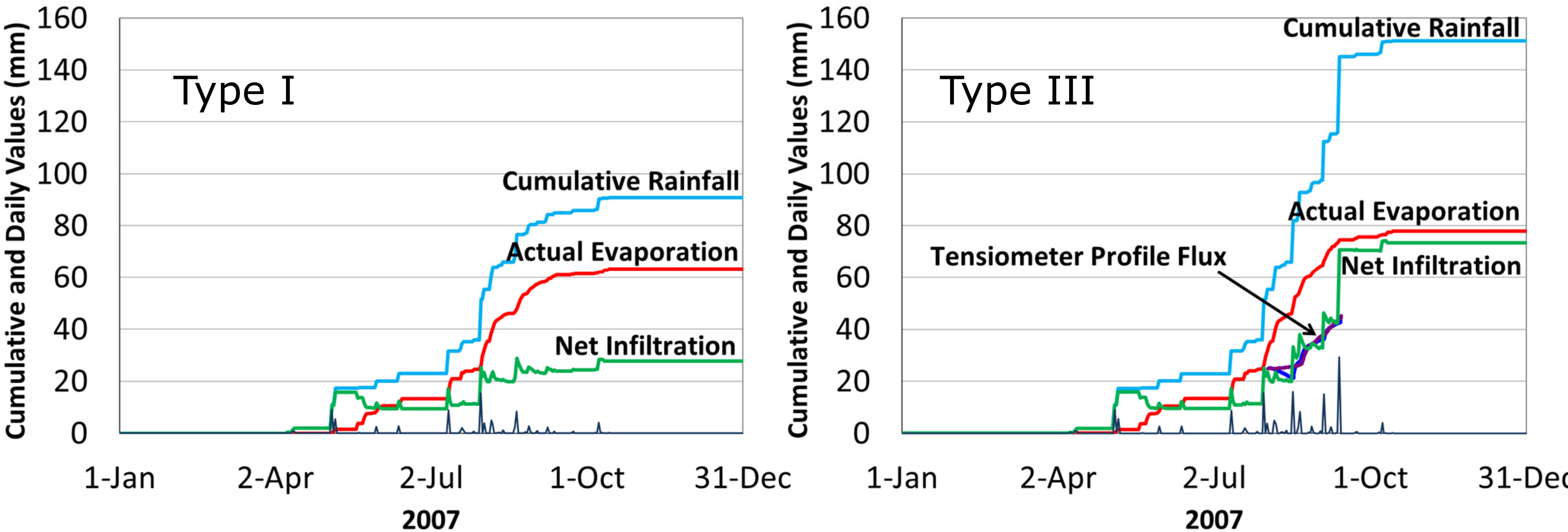
FAO-Model results





Year	AZL with Min %NI	AZL with Max %NI	FAO Calculation
2008	35%	54%	46%
2009	8%	15%	10%
2010	38%	43%	29%

FAO-Model results



Year	Test Pile	Rainfall (mm)	FAO % Net Infiltration
2007	Type I	92	31%
2007	Type III	153	48%

Research Highlights

Thermal Regime

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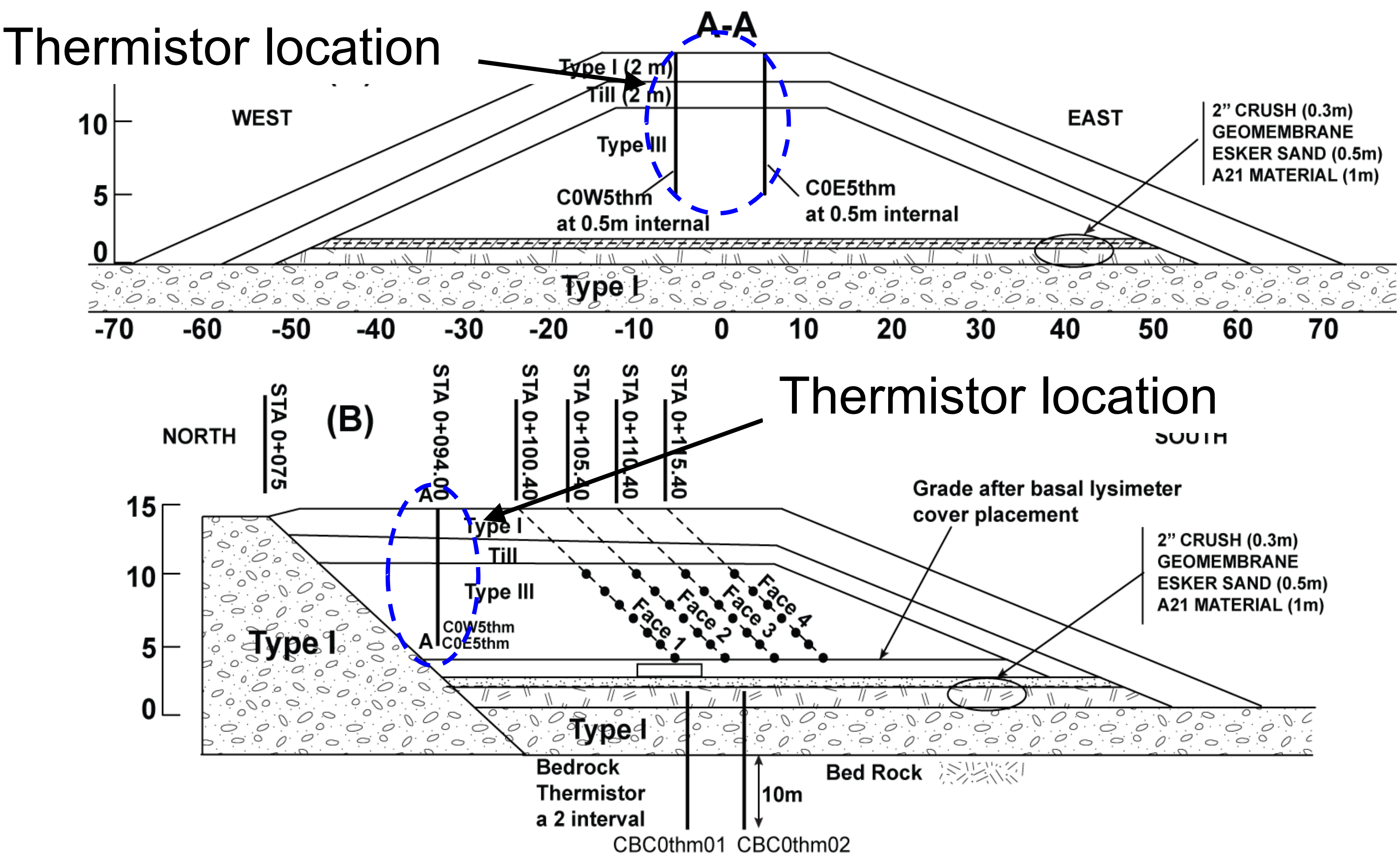
Covered test pile: Cross section A-A and Profile



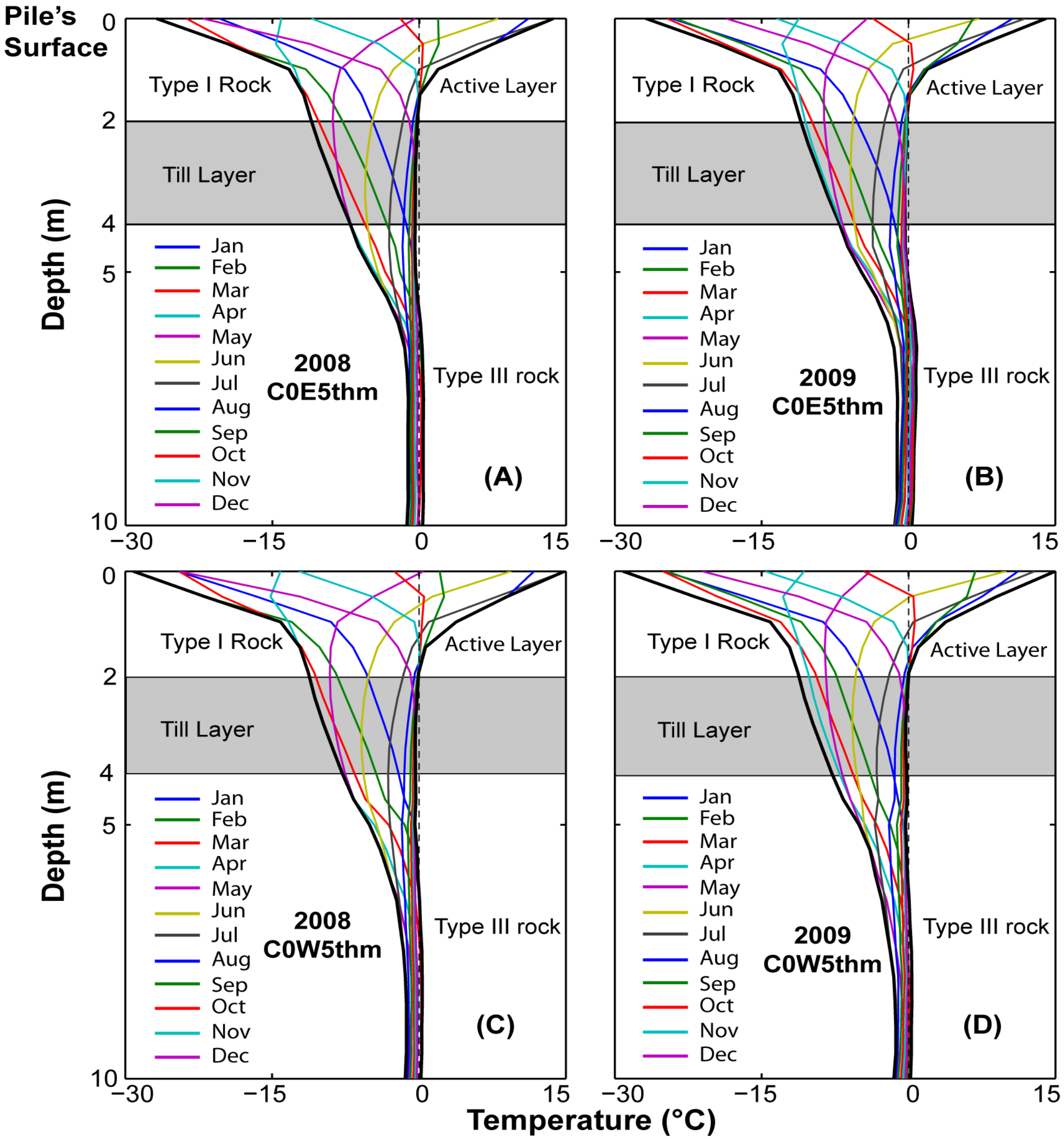
Results: Active layer thickness

➢ The active layer stays within the 2 m thick Type I waste rock cover above the till.

➢ At the top of the till layer temperatures varied between 0 °C and -12.2 °C.

➢ At the base of the till temperatures varied between 0 °C and -8.2 °C.

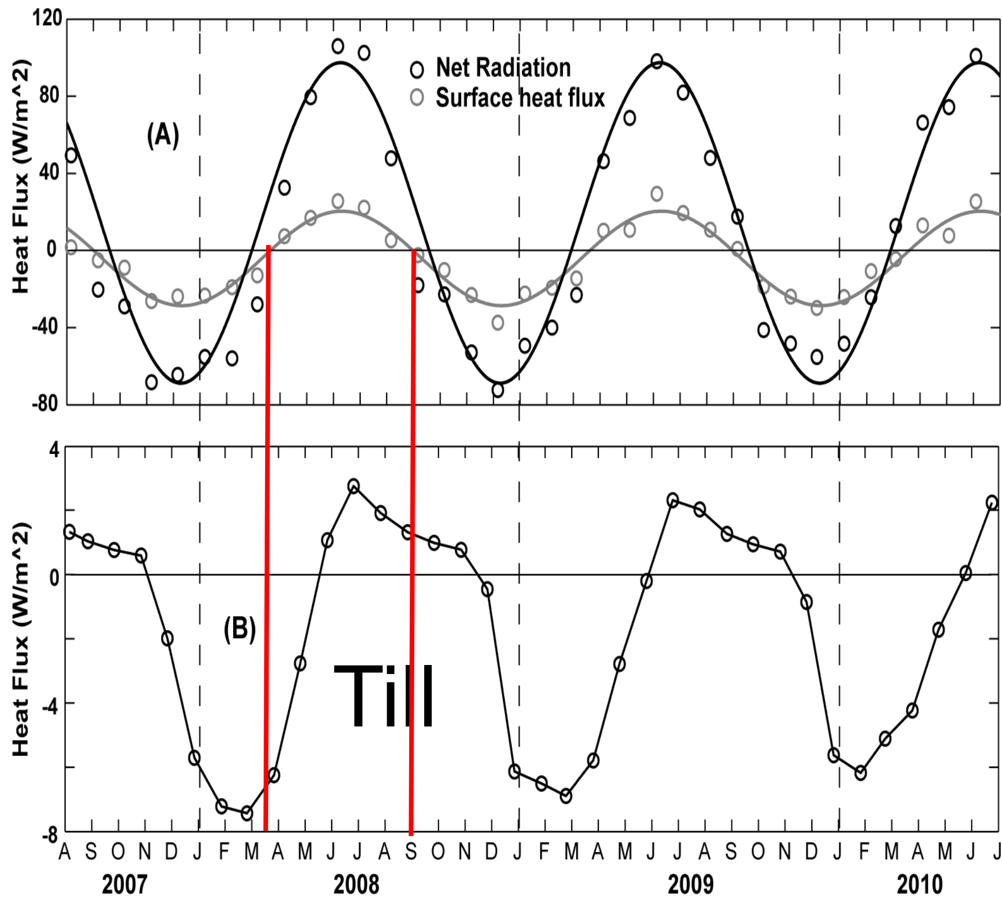
➢ Underlying Type III waste rock remains colder than 0°C year round



Results: Net radiation and heat fluxes

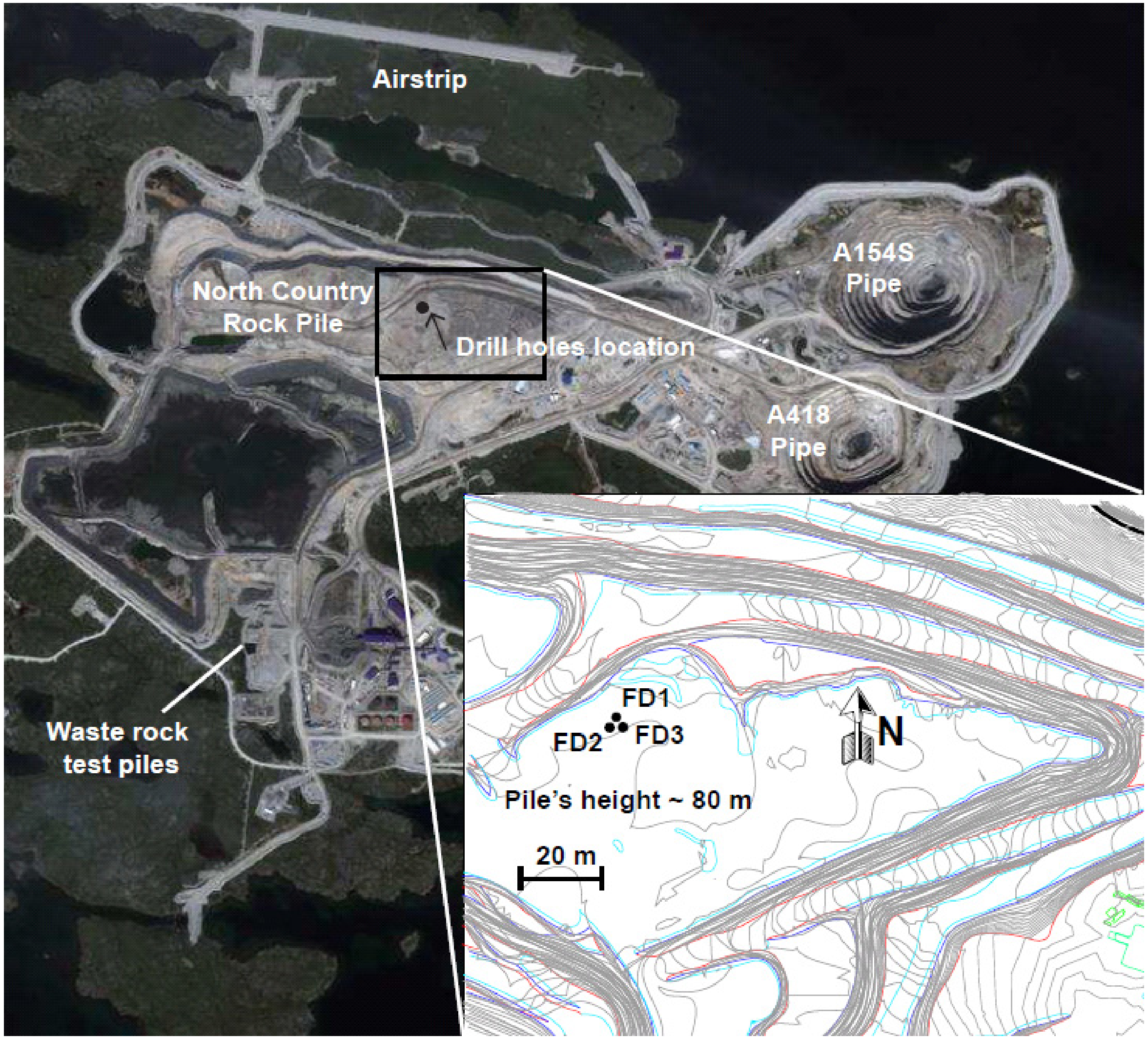
- **Net radiation**
  - Maximum value: 96.5 W m^{-2} in July
  - Minimum value: -69.7 W m^{-2} in mid Dec.
  - R_n (W m^{-2}) = 13.4 + 83.1sin(2pt/365 - 1.30)
- **Ground surface heat flux:**
  - Maximum: 20.4 W m^{-2} in July
  - Minimum: -28.6 W m^{-2} in mid Dec.
  - The fitting curve: G = -4.1 + 24.5sin(2πt/365 - 1.35)

- The mean annual heat flux across the bottom of the till: -1.78 W m^{-2} which is 43 % of mean annual surface heat flux
- Negative heat flux through the till means that heat is removed from the underlying Type III waste rock



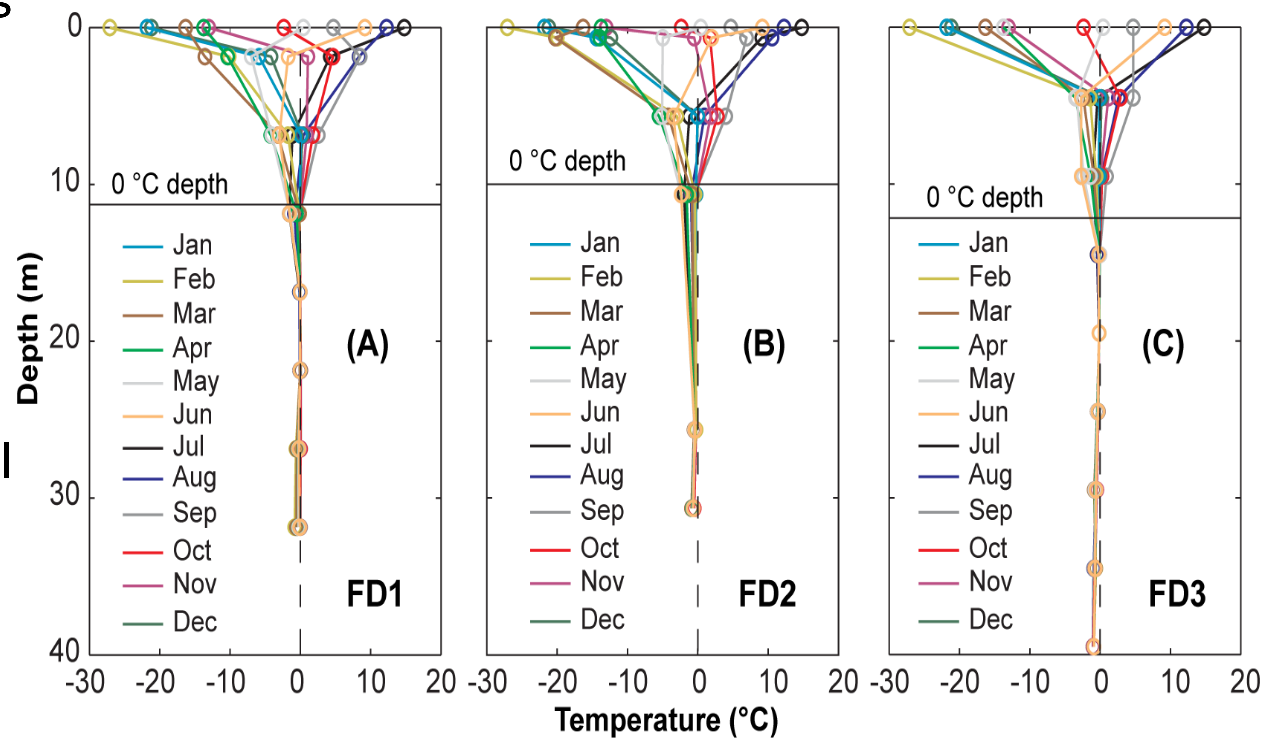
Full-Scale Thermal Regime

- 3 drill holes
  - 32, 31 and 40 m deep



Results: Ground temperatures

- ➢ Initial 0°C isotherms are at about 11 m below the surface.
- ➢ Initial depth affected by the drilling processes and temperature disturbances at the drill holes.
- ➢ The temperatures at the drill hole locations are usually warmer than undisturbed ground temperatures

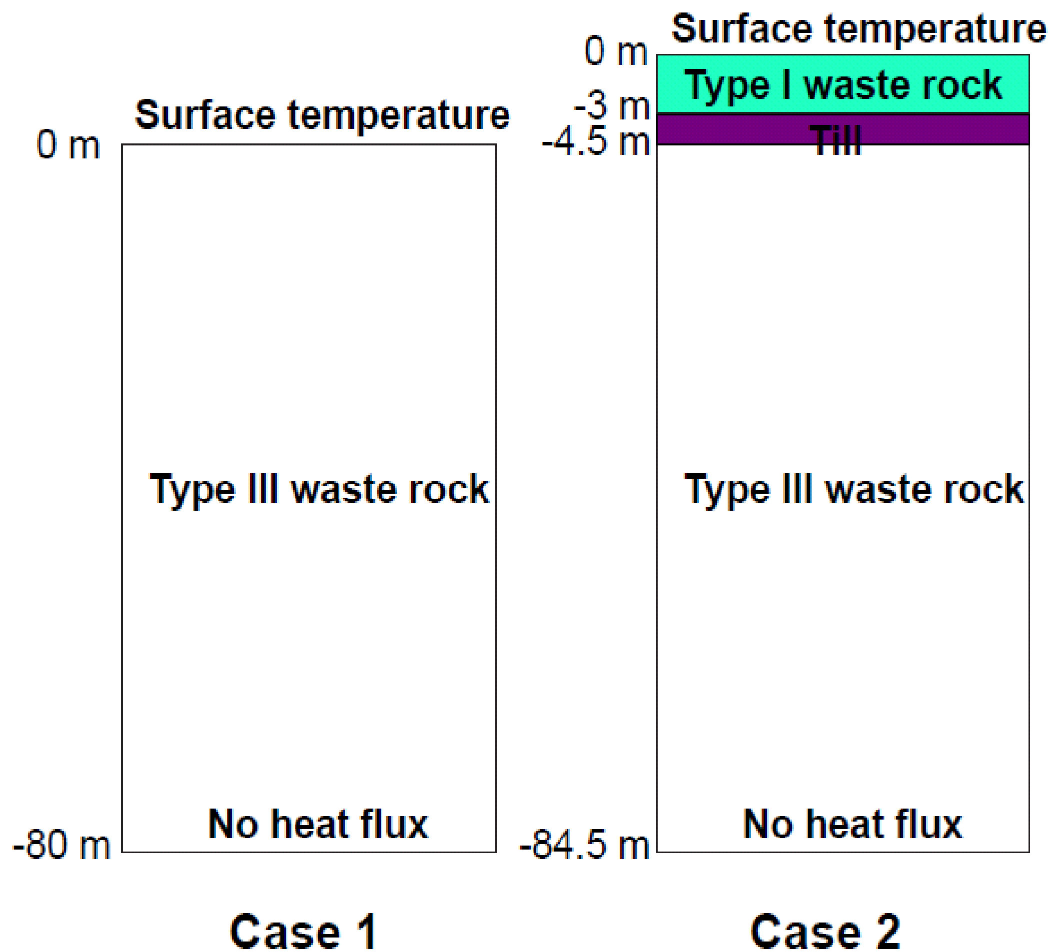


Results: Simulation

- Two cases:
- Case1: 1-D heat conduction:
- Case 2: 1-D heat conduction with 1.5-m till and 3-m Type I rock.
- Boundary conditions are no flux at the base and surface temperature
- Surface temperature

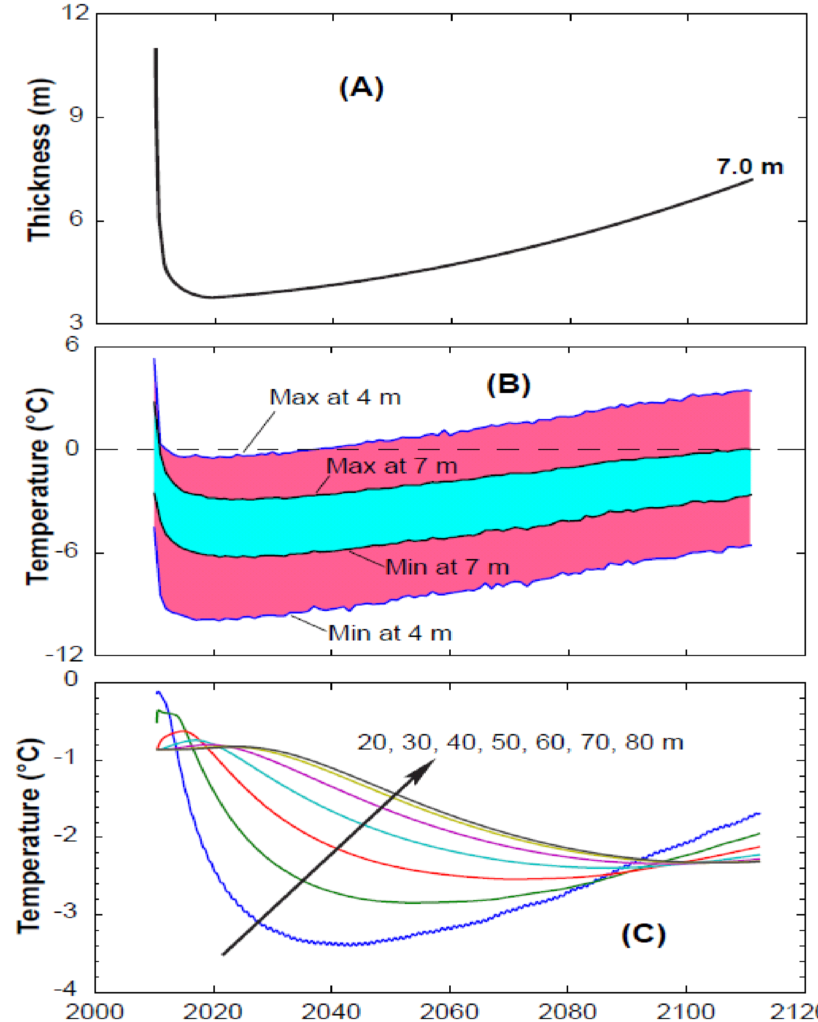
$$T_s = -6.3 + 20.3\sin\left(\frac{2\pi t}{365}\right) + \frac{0.056t}{365}$$

- Warming rate of surface temperature is 5.6°C over 100 years



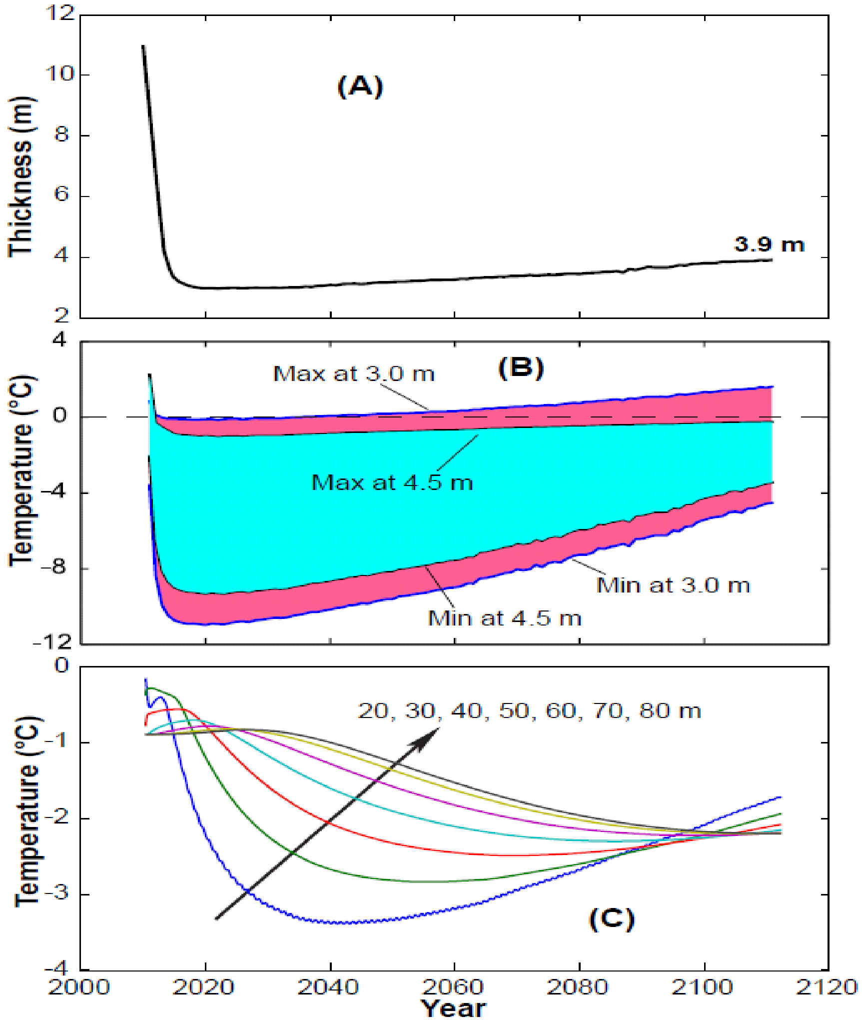
Results: Simulation (Case 1 – Uncovered)

- Active layer thickness dynamically changes with time and is at 7m after 100 years due to the warming climate
- It reaches its minimum value of 4 m in 2020 and then increases steadily to 7 m in 2110
- Maximum ground temperatures at 4m and 7m reach 0°C in 2040 and 2110 respectively.
- Below 20m, ground temperatures show no annual variations and the changes are due to warming climate.
- At greater depths, the impacts of warming climate come later.



Results: Simulation (Case 2 – Covered Pile)

- Active layer is at 3m (top of the till) for the period between 2020 and 2040, however, its thickness increases to 3.9m (within till layer) in 2110.
- Maximum ground temperature at 3m (top of the till) is above 0°C after 2040 due to warming climate.
- Ground temperatures below 20 m are similar to the case 1



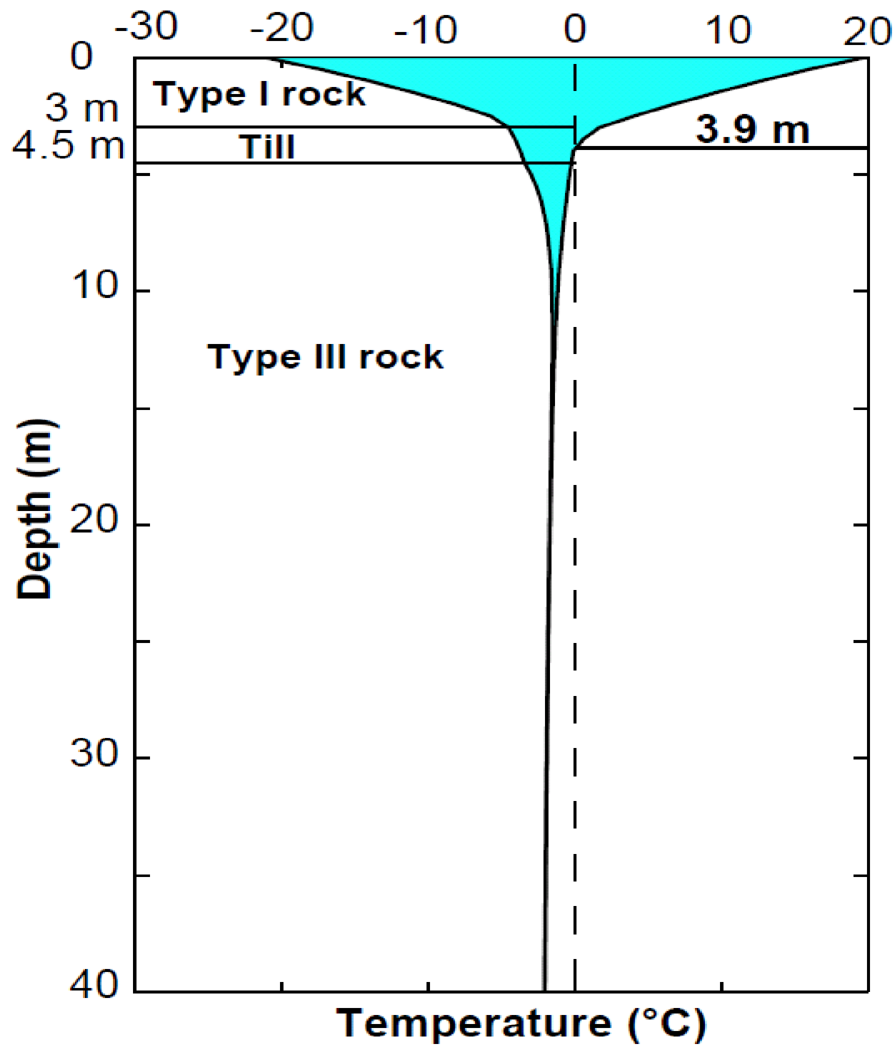
Results: Simulation (Case 2 – Covered Pile)

- Trumpet curve of ground temperatures of the waste dump indicates:

- Active layer is at 3.9 m depth which is 0.9 m into the till

- Without warming climate, the active layer will be contained within the Type I rock.

- The Type III rock below the till stay below 0°C (about -2.5°C) under the proposed climate change.



Research Highlights

Geochemistry

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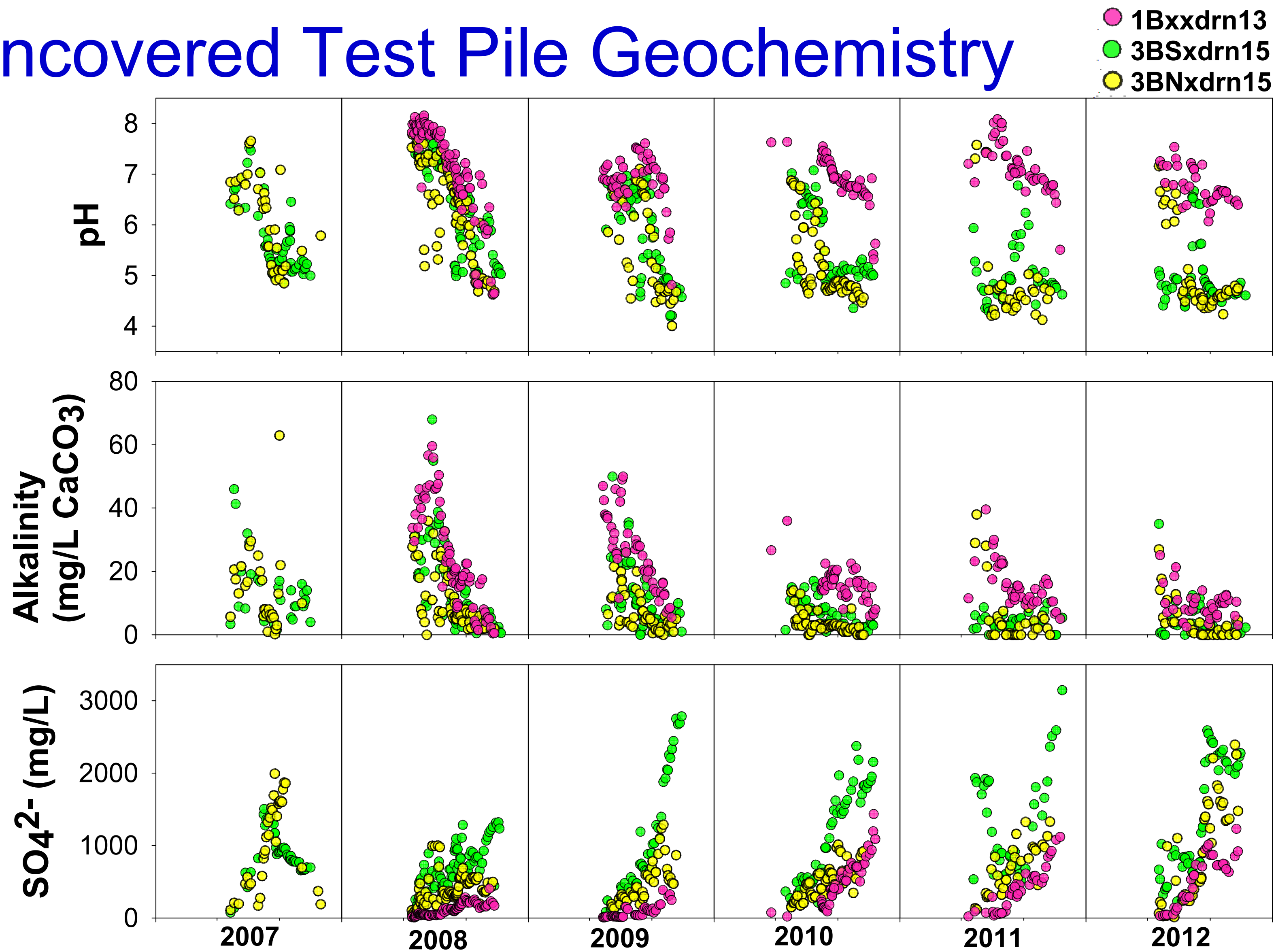
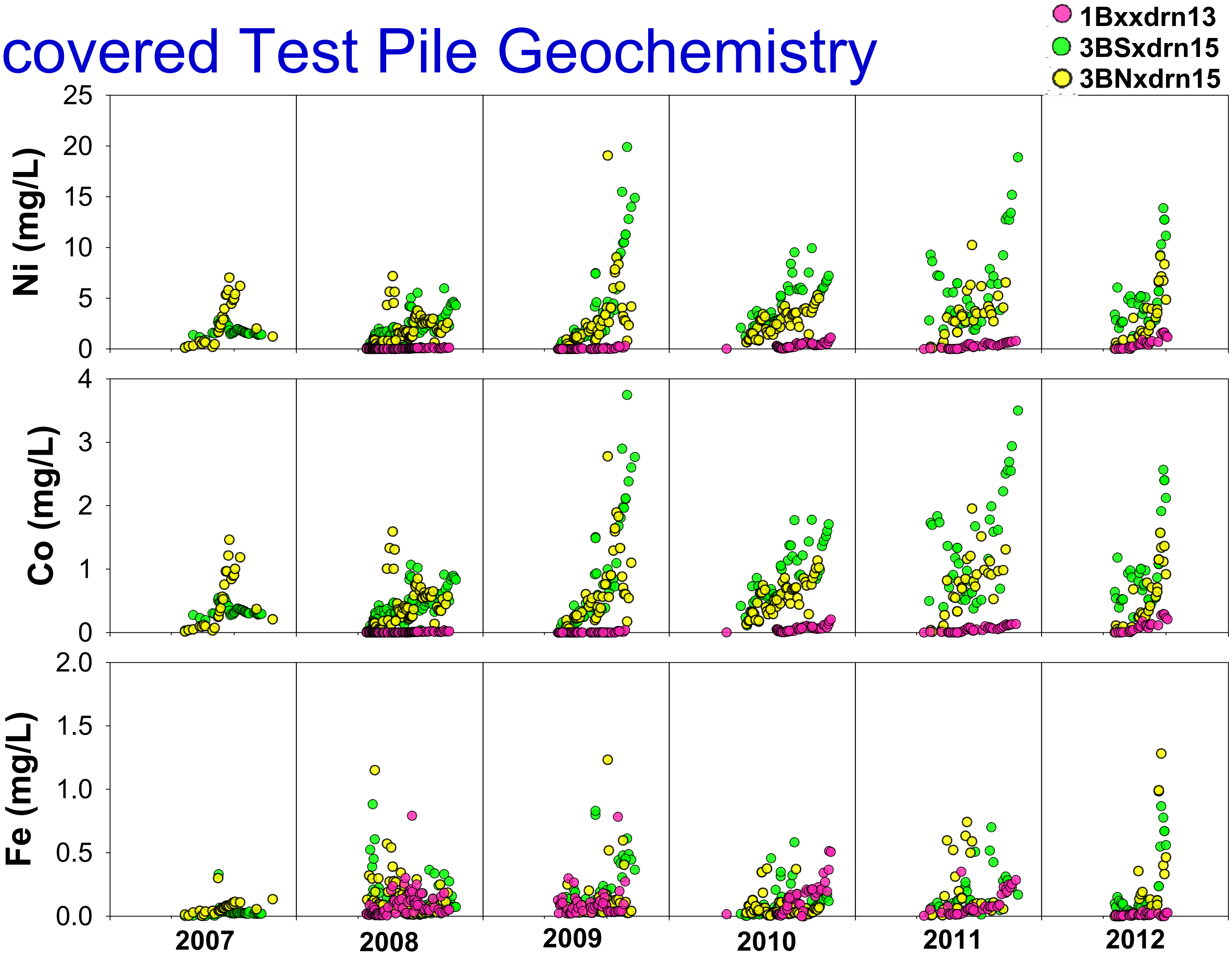
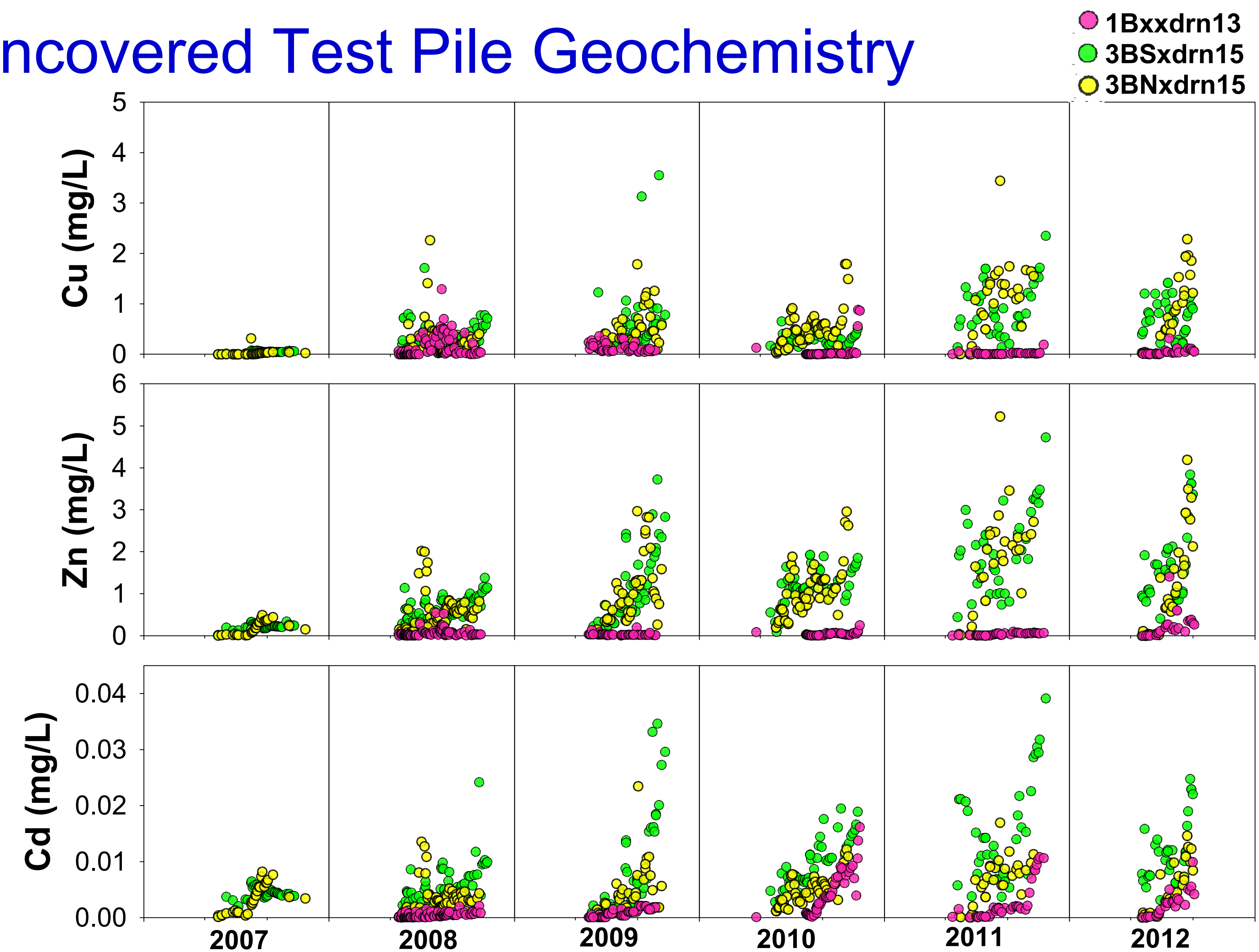
Uncovered Test Pile Geochemistry



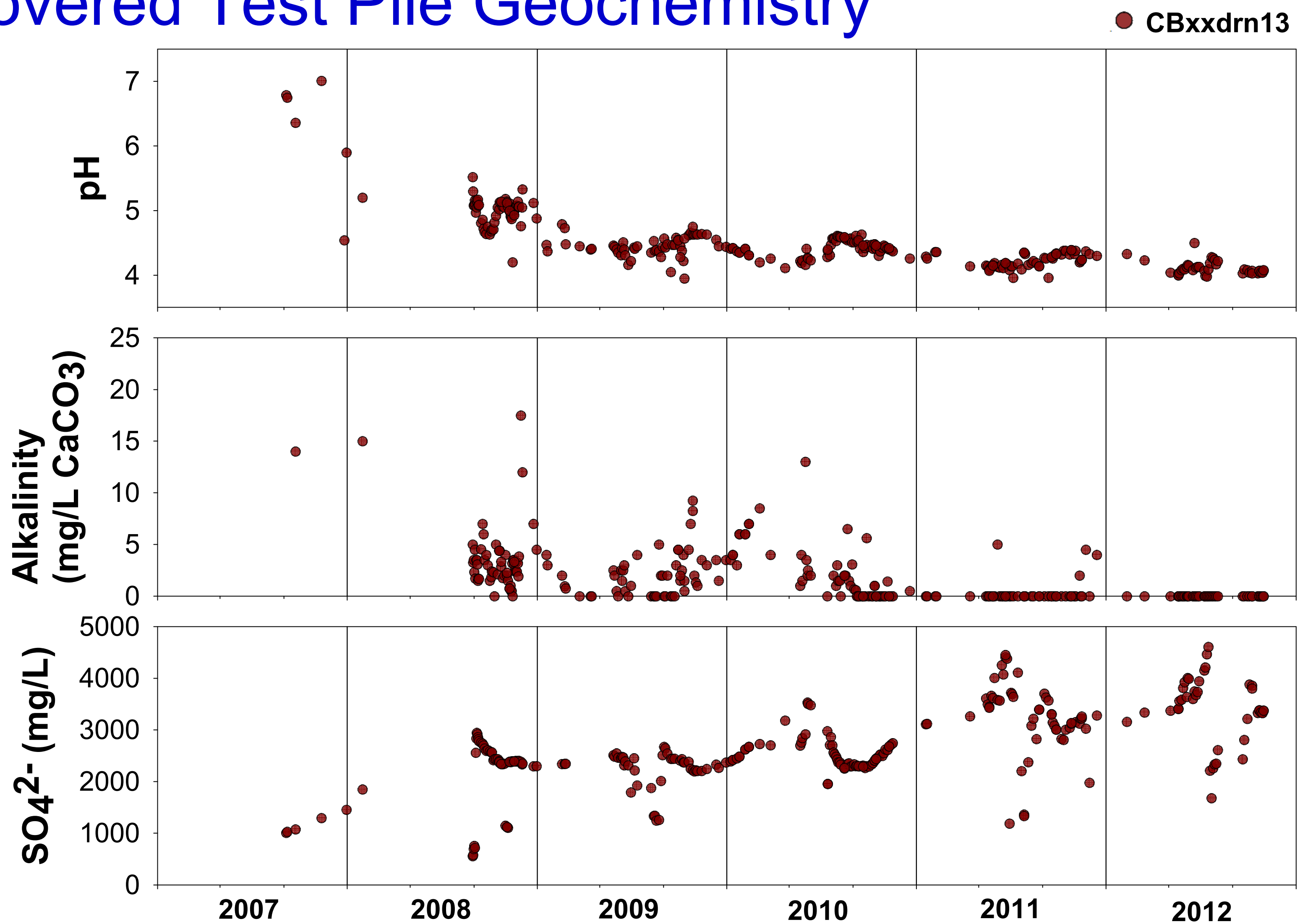
Uncovered Test Pile Geochemistry



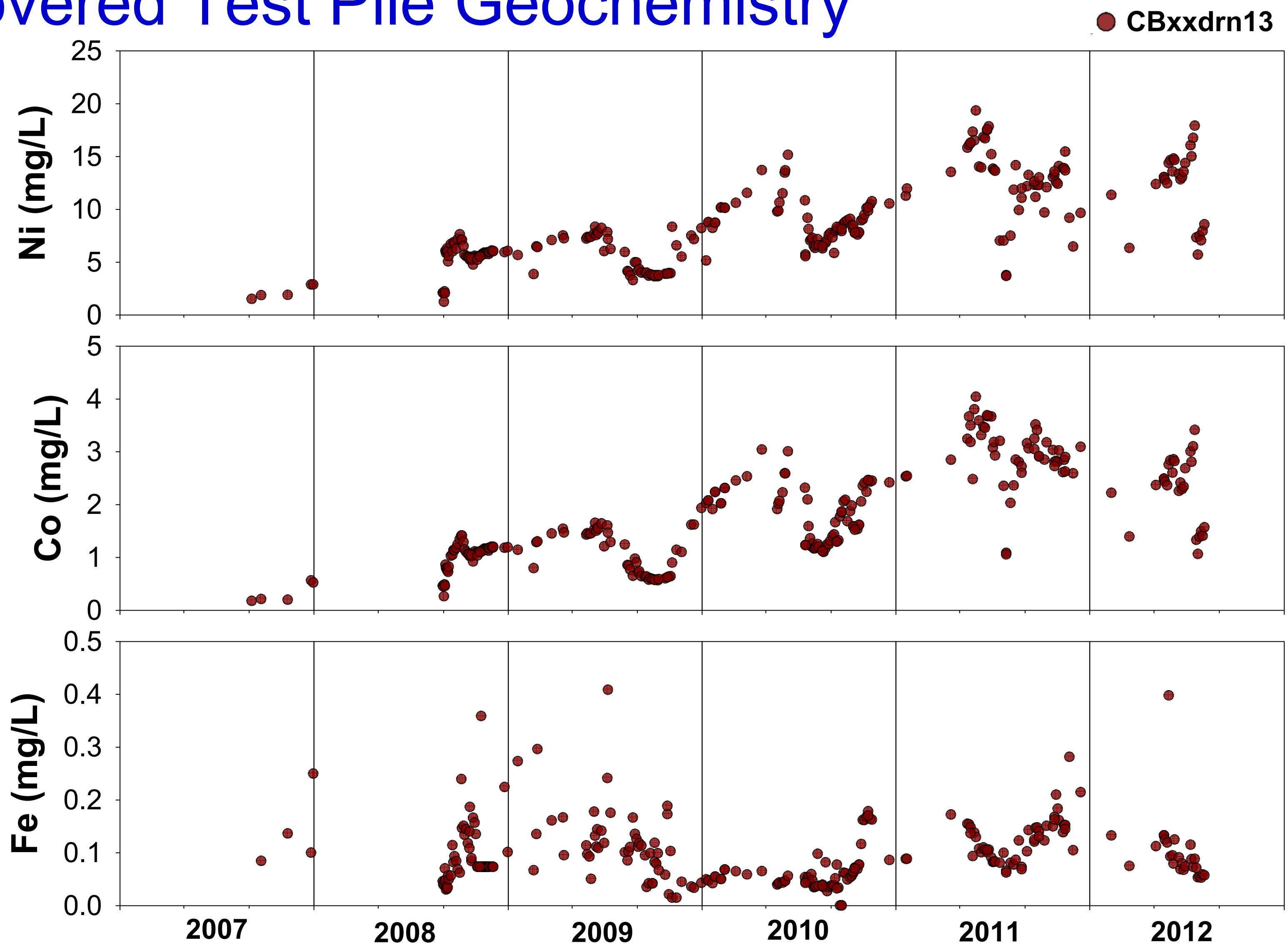
Uncovered Test Pile Geochemistry



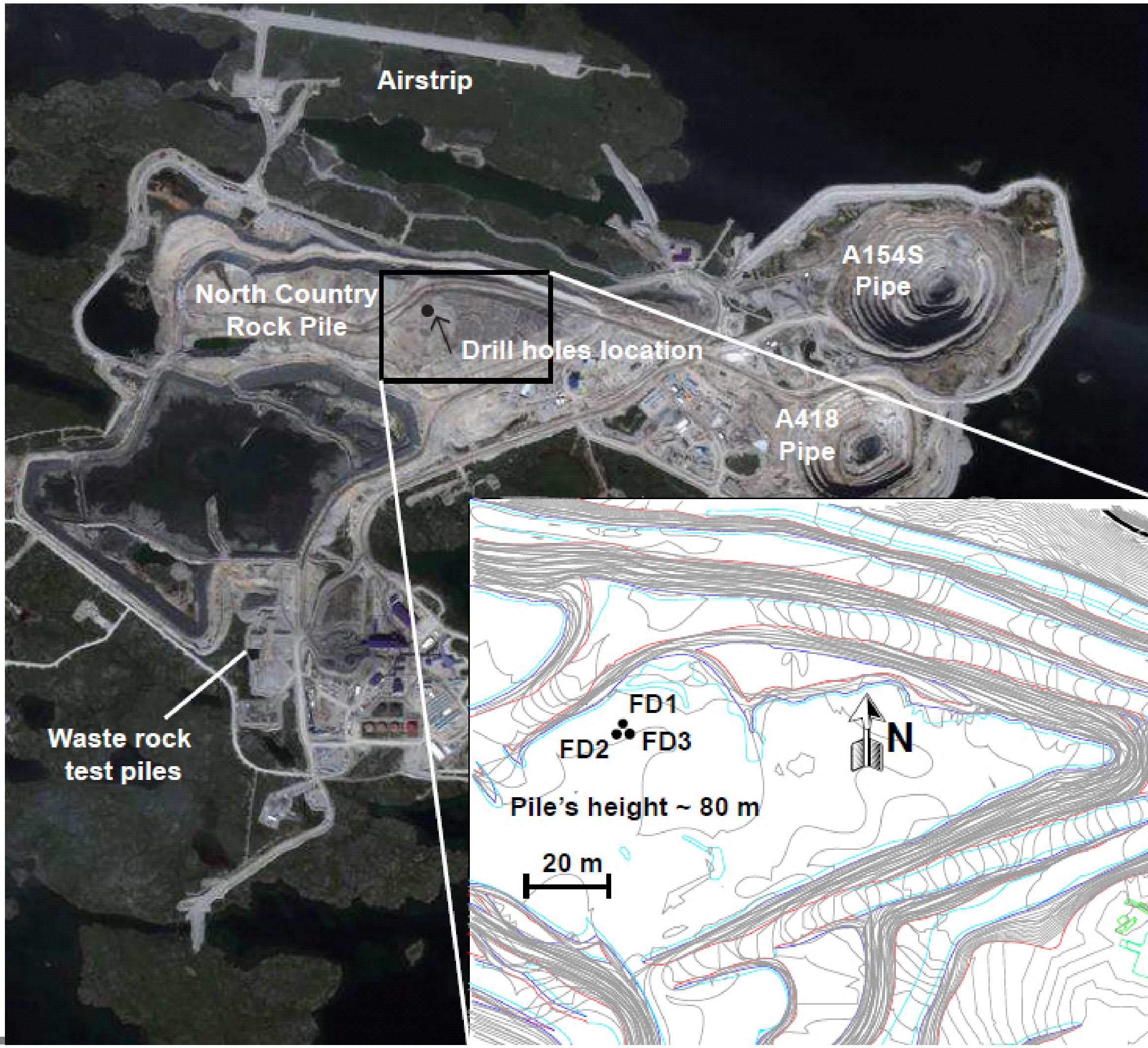
Covered Test Pile Geochemistry

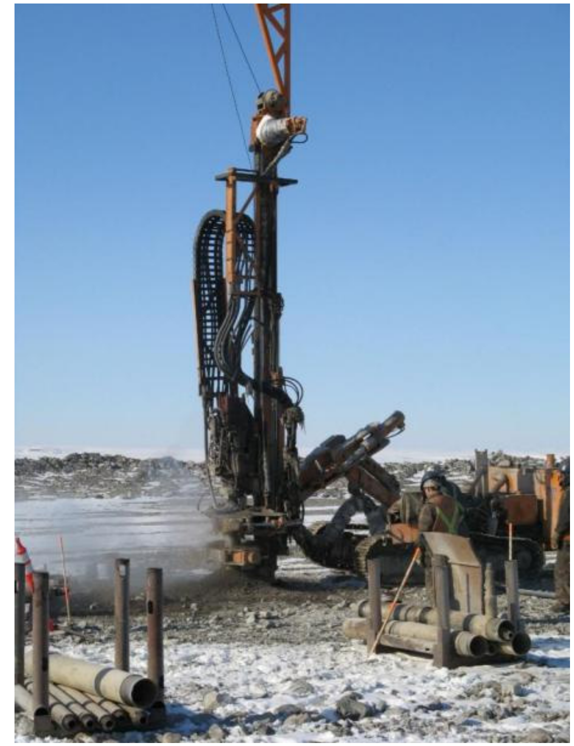


Covered Test Pile Geochemistry



Sulfide Mineral Weathering: Full-Scale Dump





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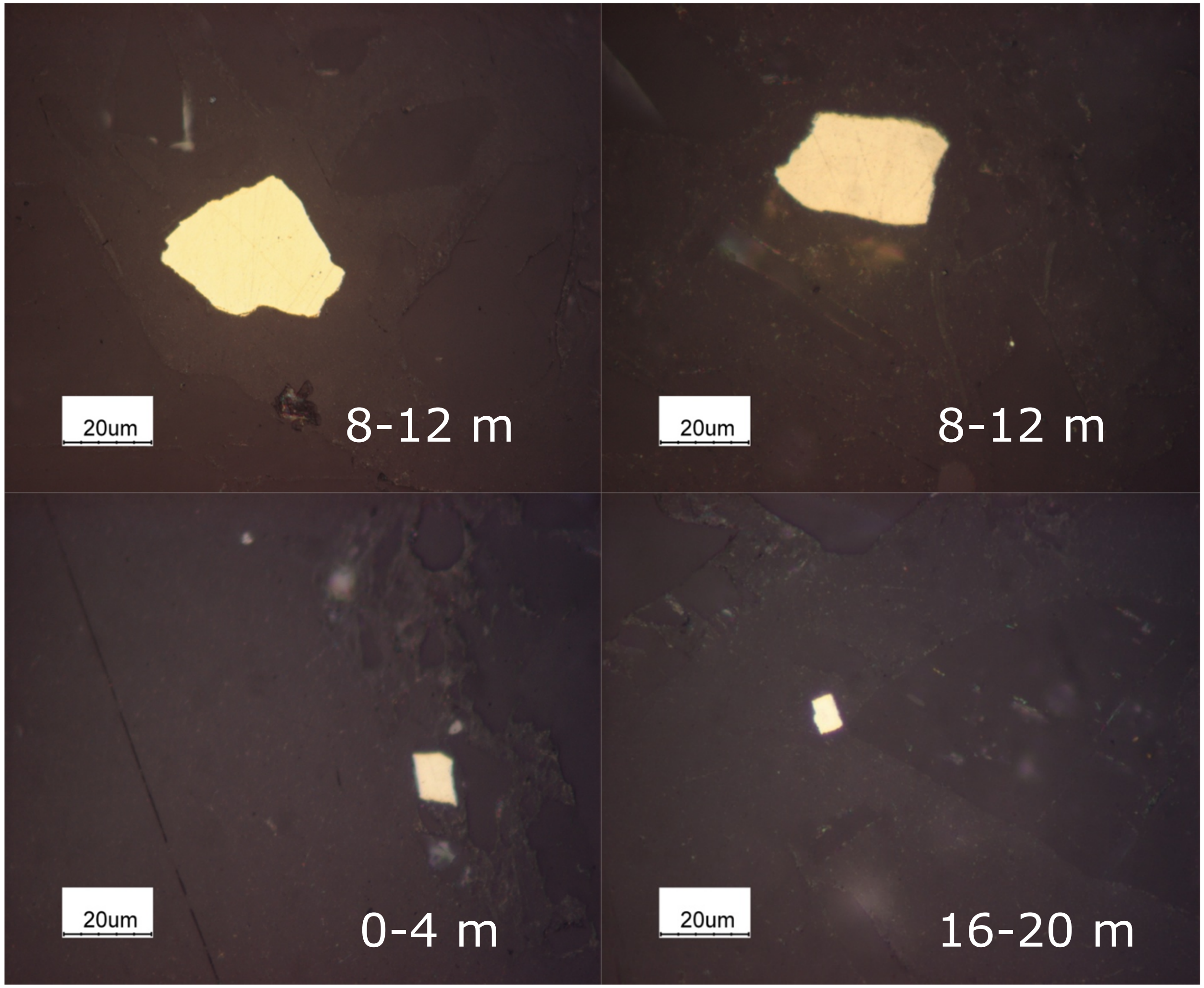

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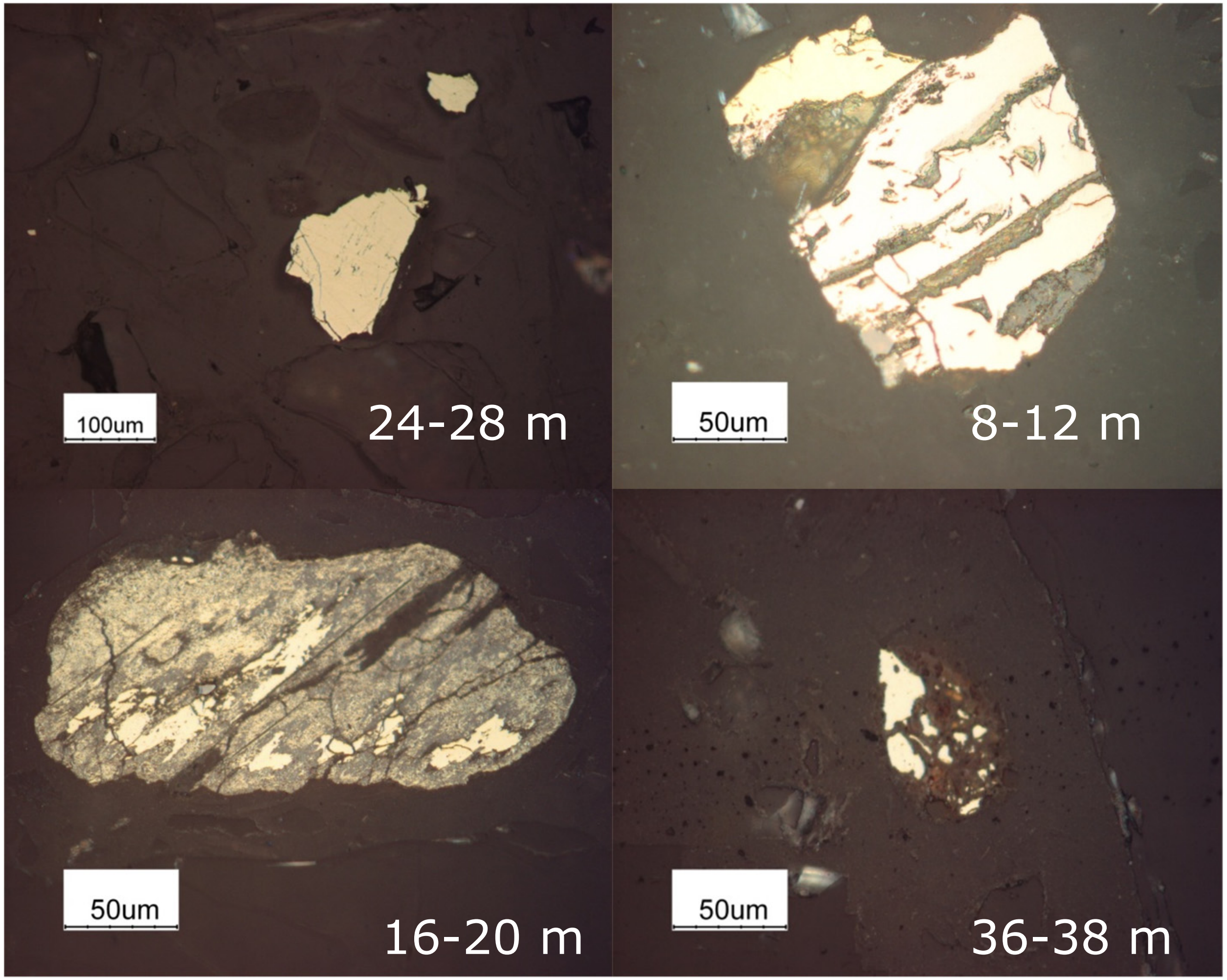
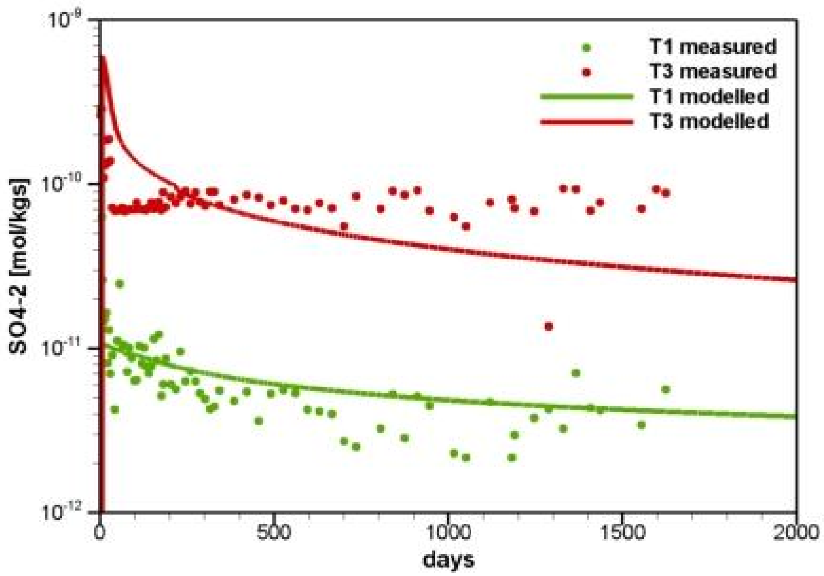


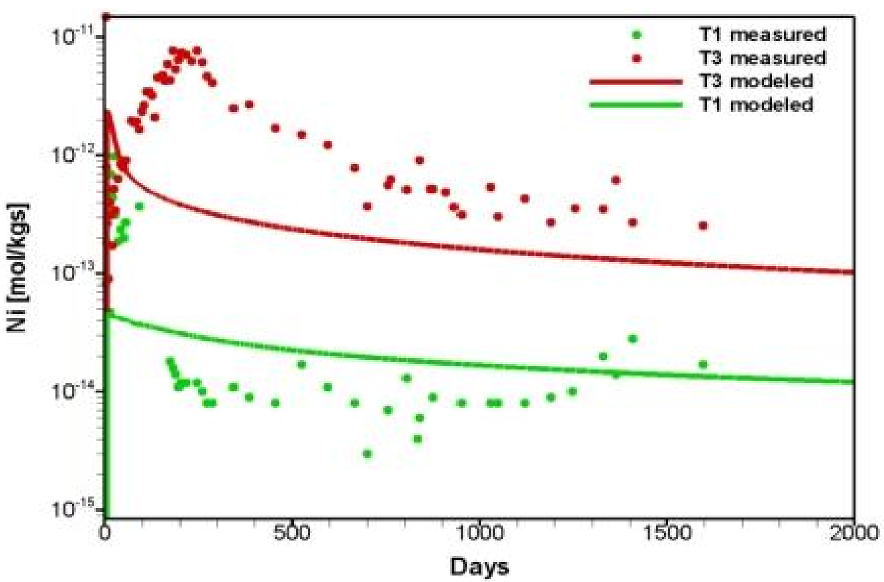
Research Highlights

Scale-up

Scale-up Calculations

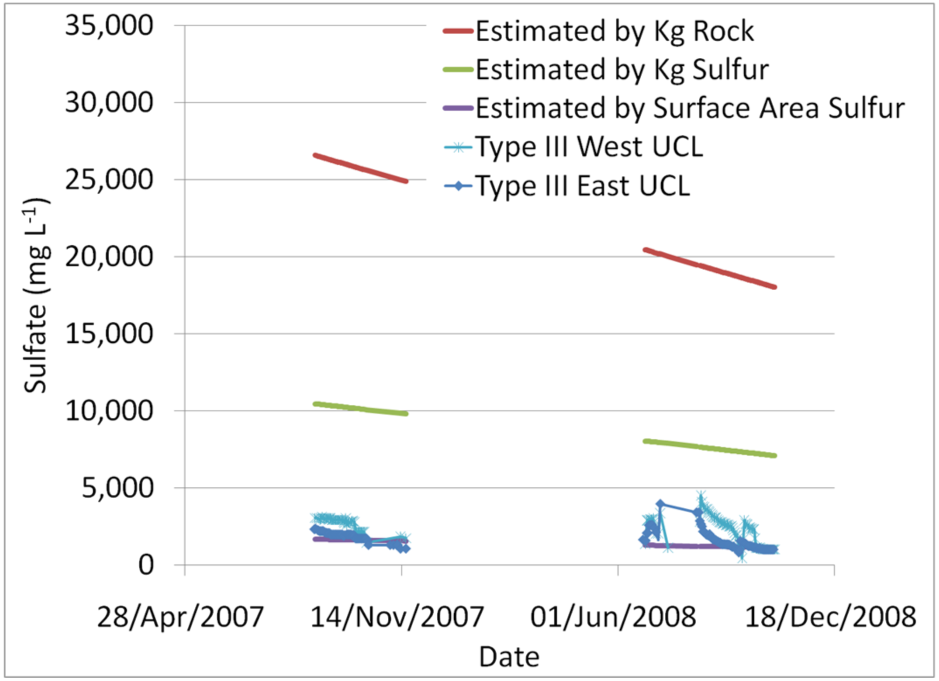
- Reactive transport modelling of humidity cell experiments
  - Develop robust conceptual model of sulfide mineral oxidation and geochemistry to be applied to larger scales
  - Calibrate model to sulfide content, mineral surface area and temperature effects
  - Only measurable parameters adjusted in input files
  - Additional calibrations underway





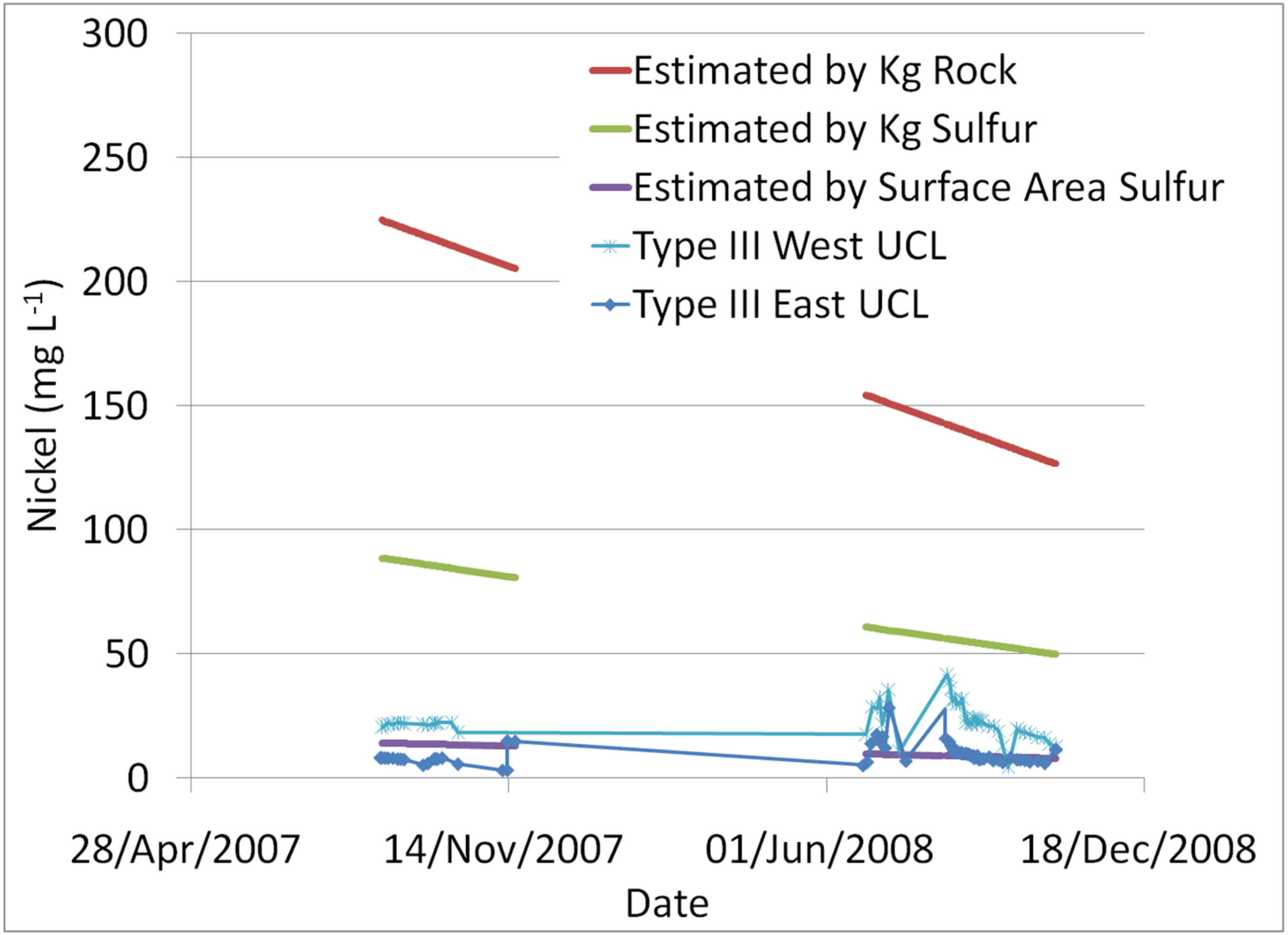
Scale-up Estimates

- Concentration calculations based on:
  - Reaction rates from humidity cell experiments
  - Rates scaled to weathering age of rock
  - Estimated residence time
- Estimates normalized to
  - Mass of rock
  - Mass of solid phase sulfur
  - Estimated surface area of solid phase sulfur
- No temperature correction
- Simple residence time estimate

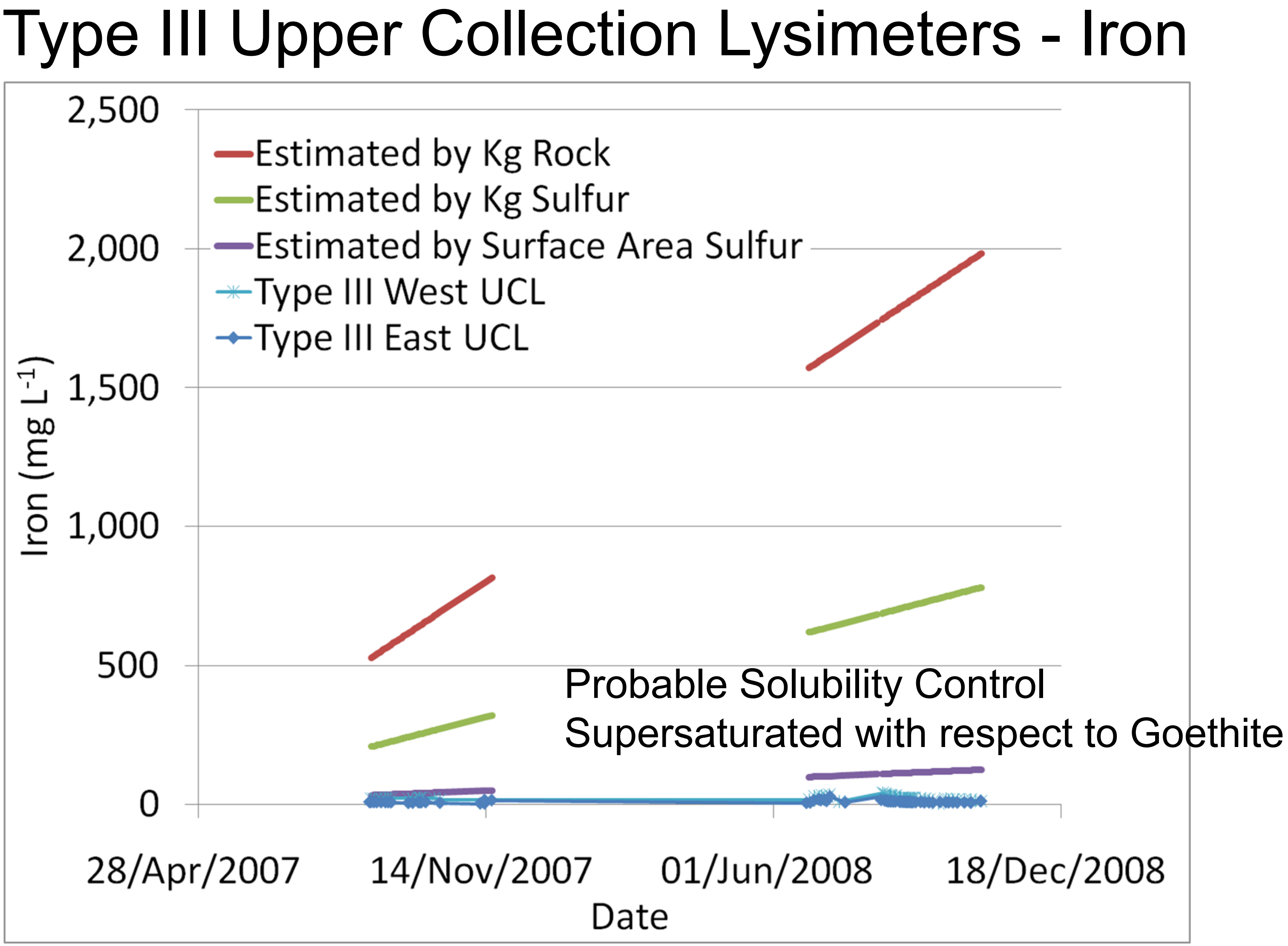


Concentration Estimates

Type III Upper Collection Lysimeters - Nickel



Concentration Estimates



Thank You!

Questions?

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