Part 2: Reactive Transport Modeling in Mine Waste Management – Where to from Here?

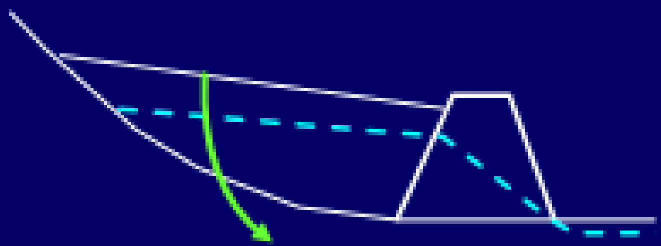
Mayer, U, Amos, R, Wilson, D, Blowes, D, Su, D, Seigneur, N, Raymond, K, Yi, X.

December 5, 2019

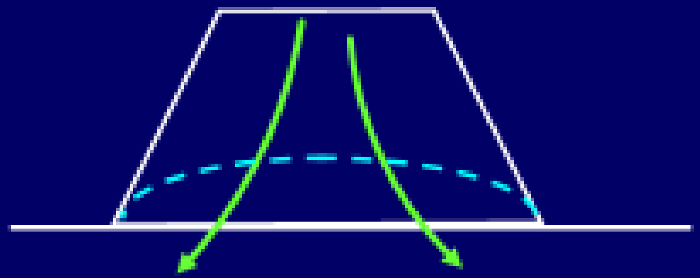
THE UNIVERSITY OF BRITISH COLUMBIA

Mine Waste Environments

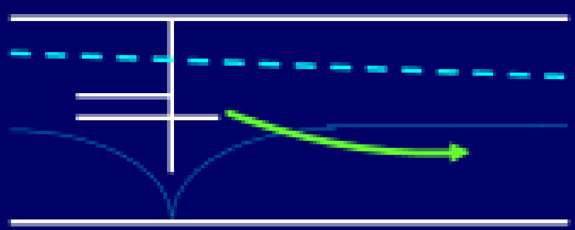
Mine Tailings



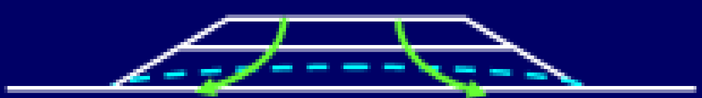
Waste Rock Piles



Decommissioned Underground Mines



Decommissioned Heap Leach Pads

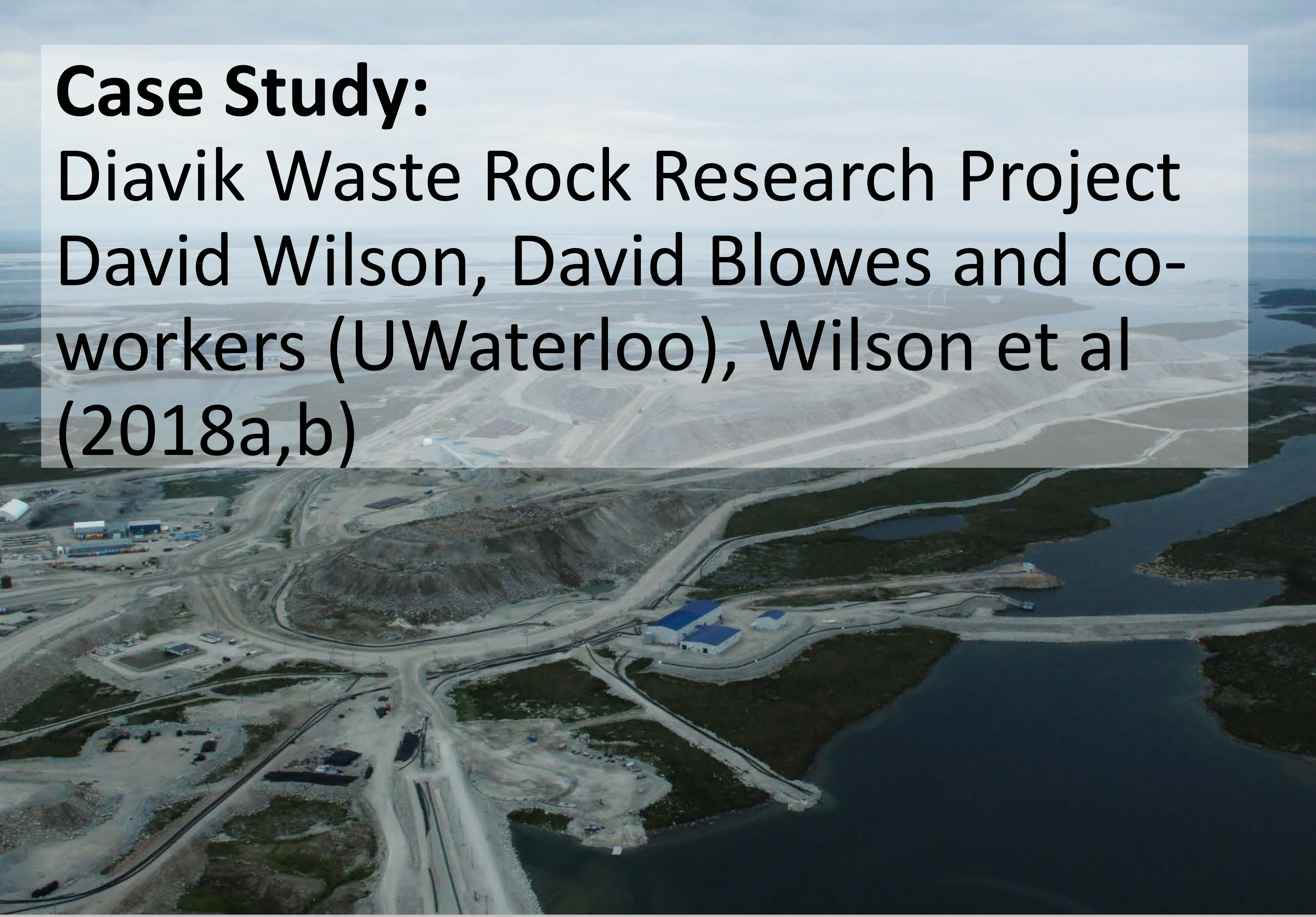


RTM Examples Related to Waste Rock

- **Case Study**:
  - **Diavik Waste Rock Research Project** - reactive transport model (RTM) to identify **scaling relationships** for ARD from **laboratory experiments** to **full-scale piles**

Case Study:

Diavik Waste Rock Research Project David Wilson, David Blowes and co-workers (UWaterloo), Wilson et al (2018a,b)



Mechanistic scale-up

Humidity Cells

0.1 m (1 kg)

Active Zone Lysimeters

2 m (9,300 kg)

Test Piles

15 m (8.2 x 10^7 kg)

Full Scale Pile

80 m (1.2 x 10^{11} kg)

Wilson et al (2018a,b)

Hypothesis: RTM can be *used to implement* an integrated conceptual model of sulfide waste rock weathering for laboratory experiments (i.e. humidity cells), then *scaled* to assess the geochemical evolution of a waste rock pile (i.e. full scale pile).

Humidity Cells

Temperature

Constant: 22 °C and 5 °C

Hydrology

Constant: 500 mL wk^{-1}

Geochemistry

Gas:

- Atmospheric P_{O_2}, P_{CO_2}

Liquid:

- DI

Solid:

- Sulfides: pyrrhotite, chalcopyrite, sphalerite, pentlandite (total 0.18 wt.% S)
- Host: calcite, dolomite, biotite, muscovite, albite
- Secondary: jarosite, ferrihydrite, gibbsite, amorphous silica, gypsum, siderite

Test Piles

Temperature

Spatially and temporally variable average daily temperature

Hydrology

Temporally variable FAO-PM calculated infiltration

Constant K_S and soil parameters from characterization of site materials

Flow stopped under freezing conditions

Geochemistry

Gas:

- Atmospheric P_{O_2}, P_{CO_2}

Liquid:

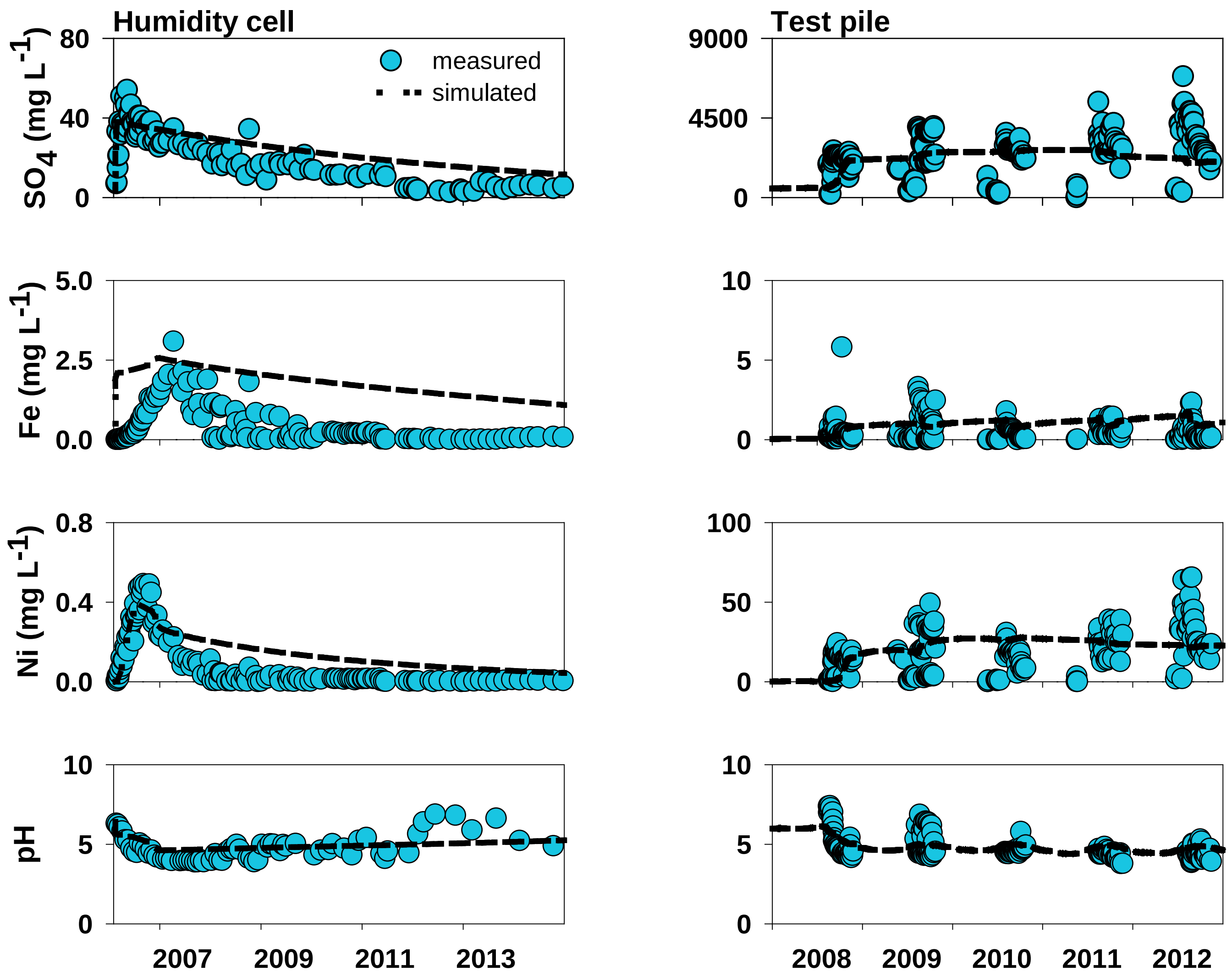
- Site precipitation

Solid:

- Sulfides: pyrrhotite, chalcopyrite, sphalerite, pentlandite
- Host: calcite, dolomite, biotite, muscovite, albite
- Secondary: jarosite, ferrihydrite, gibbsite, amorphous silica, gypsum, siderite

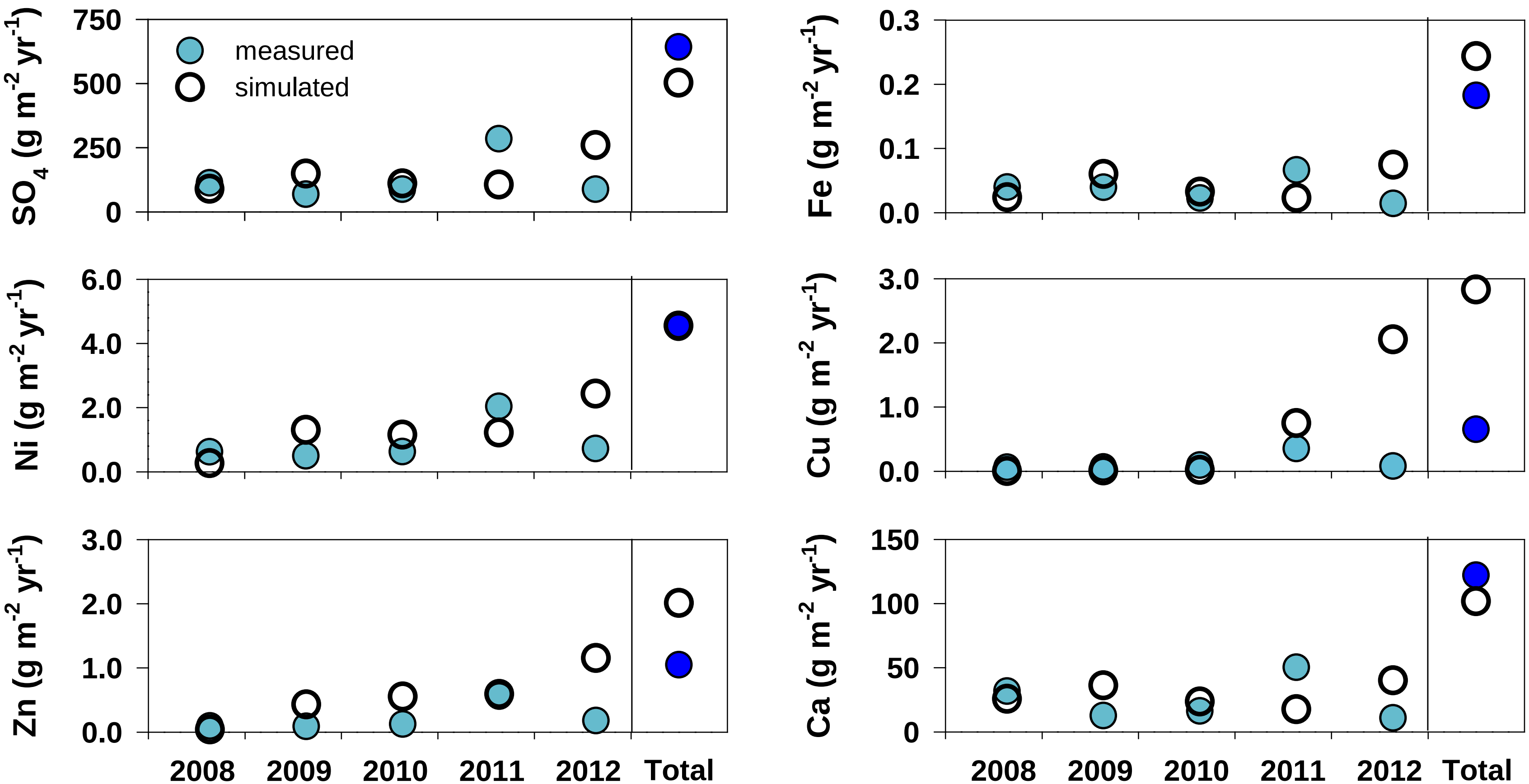
Wilson et al (2018a,b)

Geochemistry - Summary



Wilson et al (2018a,b)

Annual Mass Flux – Test Pile



Wilson et al (2018a,b)

Lessons Learned – Diavik Case Study

- A reactive transport model calibrated to laboratory experiment results can be used to provide realistic multi-year assessment of waste rock geochemical evolution on the test pile scale
  - Geochemistry identical, BUT:
  - Scale-up requires consideration of additional processes (freeze-thaw, temperature fluctuations, hydraulic response)
- Commonly measured parameters can be used to constrain the modeling (does not need to be overly complex!):
  - Mineralogy (host rocks and sulfide minerals)
  - Infiltration
  - Temperature
  - Particle size distribution

RTM Examples Related to Waste Rock

- Case Study:
  - Diavik Waste Rock Research Project - reactive transport model (RTM) to identify scaling relationships for ARD from laboratory experiments to full-scale piles
- **Scenario Analyses**:
  - Effect of **internal structure**, **heterogeneity**, and **scale** on ARD release: ***Do pile construction methods affect ARD release, and if so, how?***

Effect of internal structure, heterogeneity, and scale on ARD release

Katherine Raymond, MSc-student

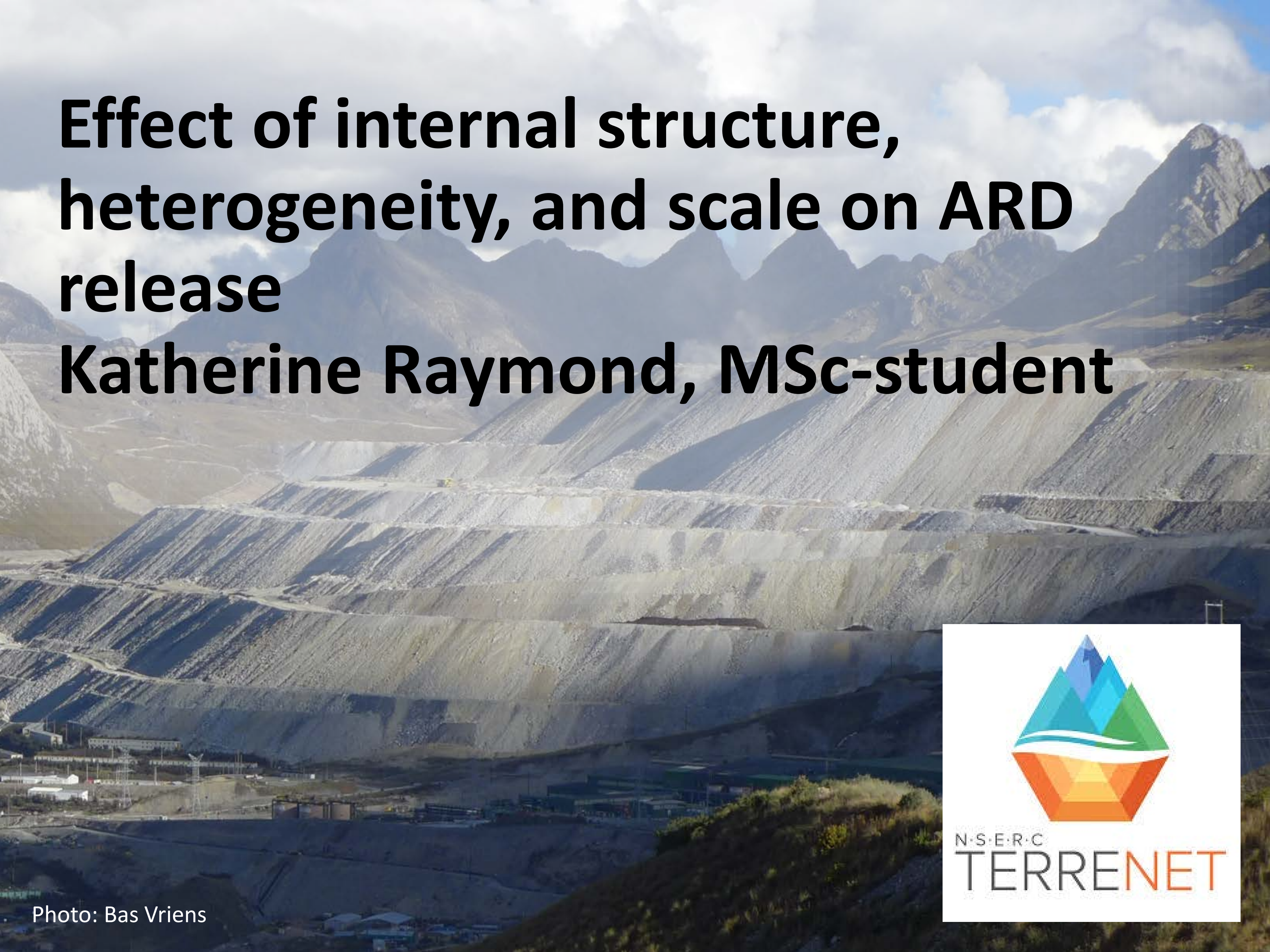
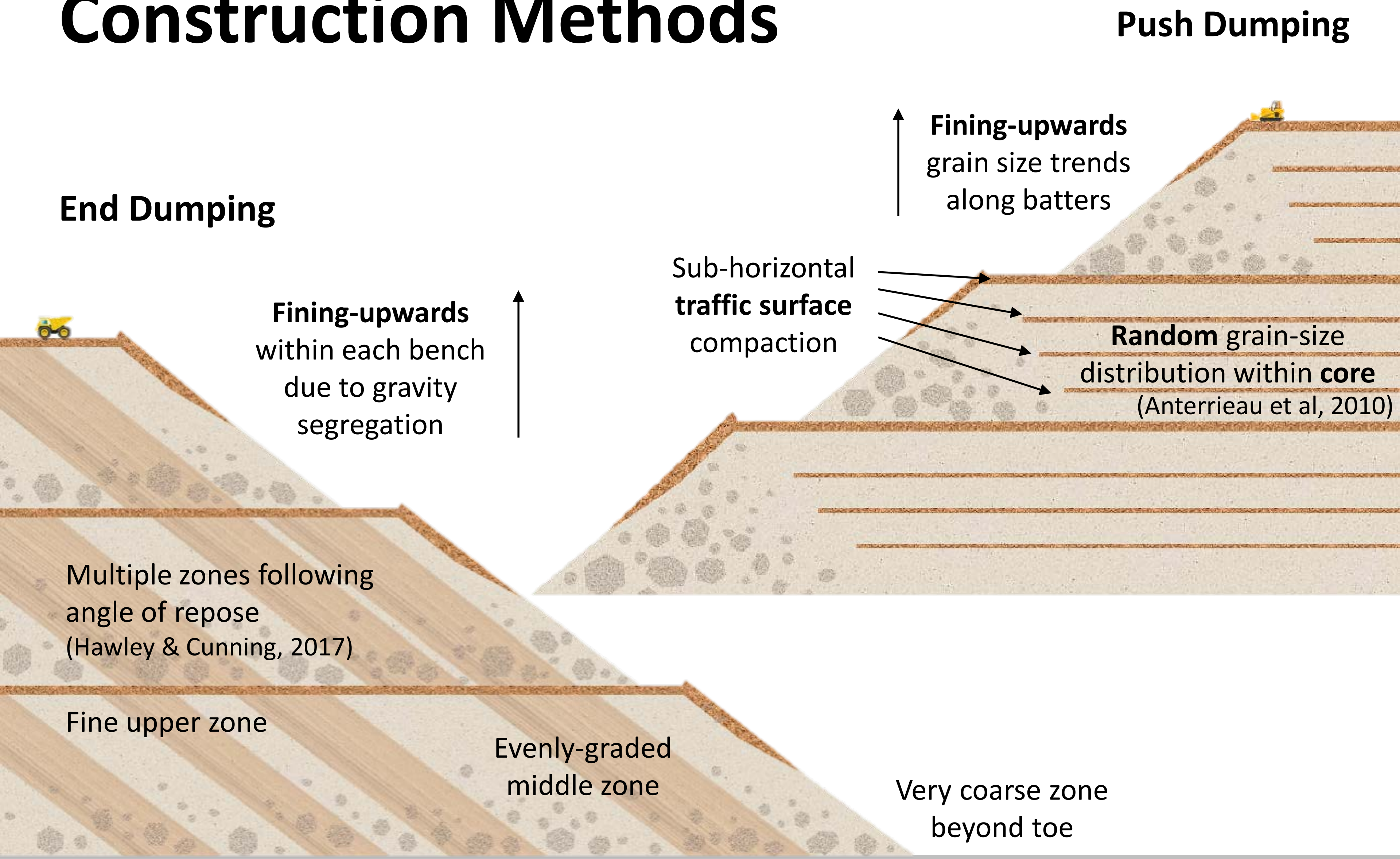


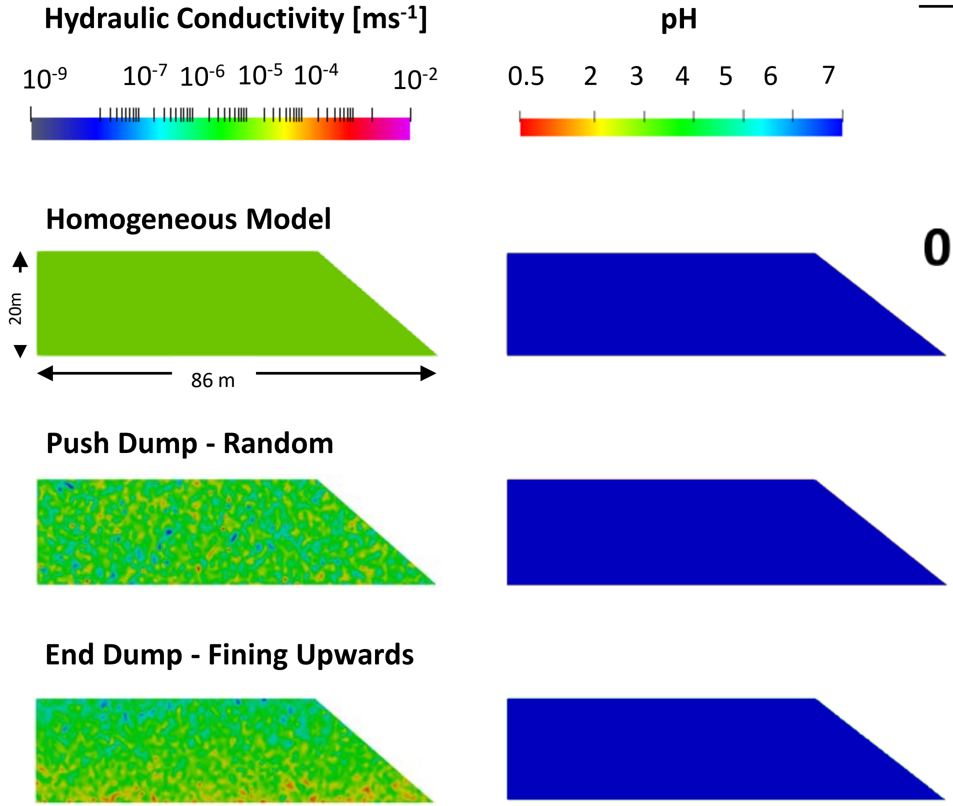
Photo: Bas Vriens

Construction Methods

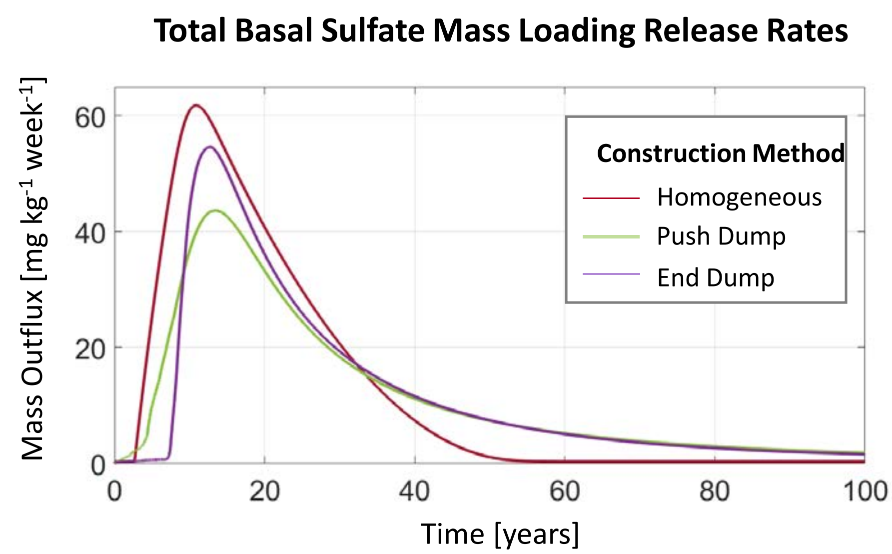


Influence of Heterogeneity and Spatial Trends

Case		Max Mass Loading Rate [$mg^{1}\ kg^{-1}\ week^{-1}$]	Decrease from Homogeneous Case
Single Bench Models			
Homogeneous		61.8	-
Heterogeneous	Push Dump	43.6	29%
	End Dump	54.6	12%
Structure	Push Dump		
	End Dump		



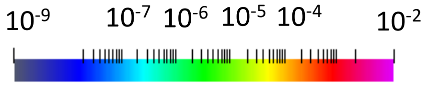
0 Years



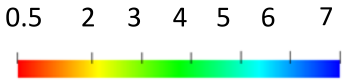
Influence of Structure (Traffic Surfaces and Trends)

Case		Max Mass Loading Rate [$mg^1\ kg^{-1}\ week^{-1}$]	Decrease from Homogeneous Case
Single Bench Models			
Homogeneous		61.8	-
Heterogeneous	Push Dump	43.6	29%
	End Dump	54.6	12%
Structure	Push Dump	**39.8**	**36%**
	End Dump	**38.4**	**38%**

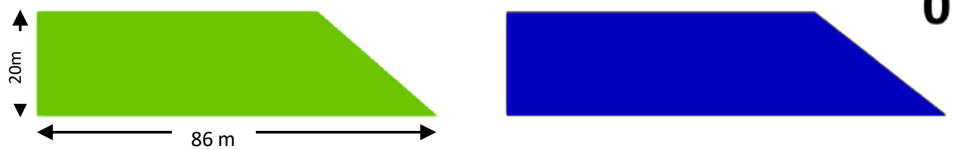
Hydraulic Conductivity [ms^{-1}]



pH



Homogeneous Model

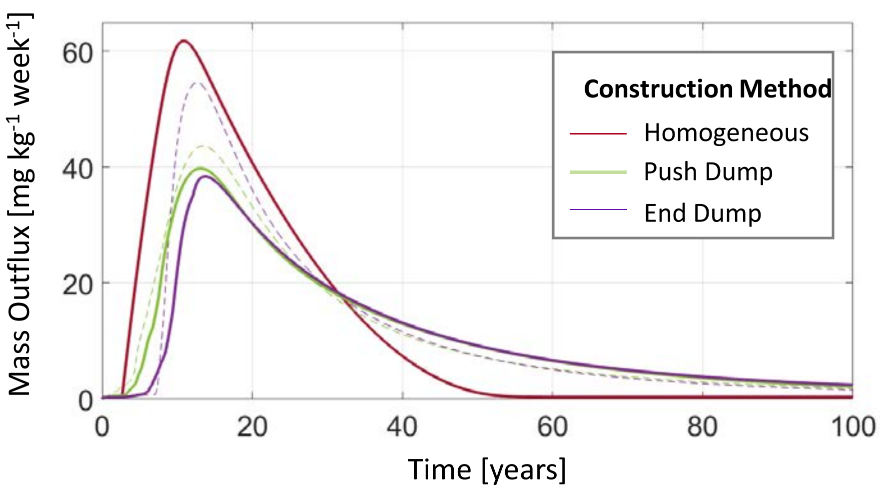


Push Dump - Random + Fining Upwards with Traffic Surfaces

End Dump - Fining Upwards + Zones with Traffic Surfaces

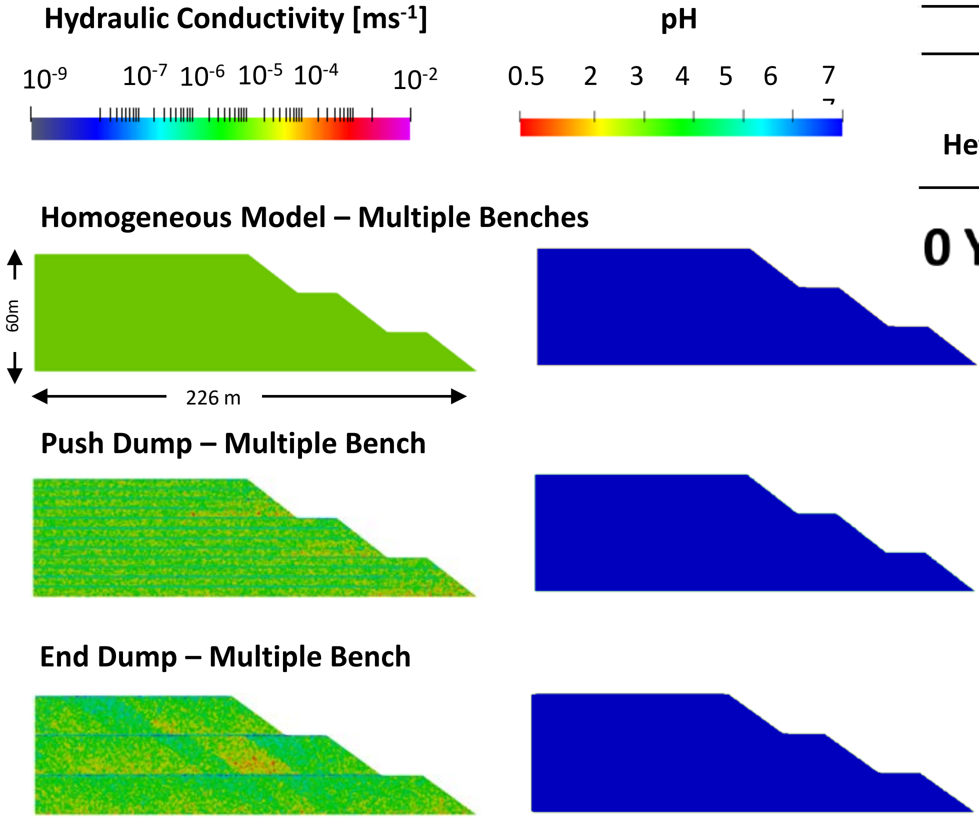
0 Years

Total Basal Sulfate Mass Loading Release Rates

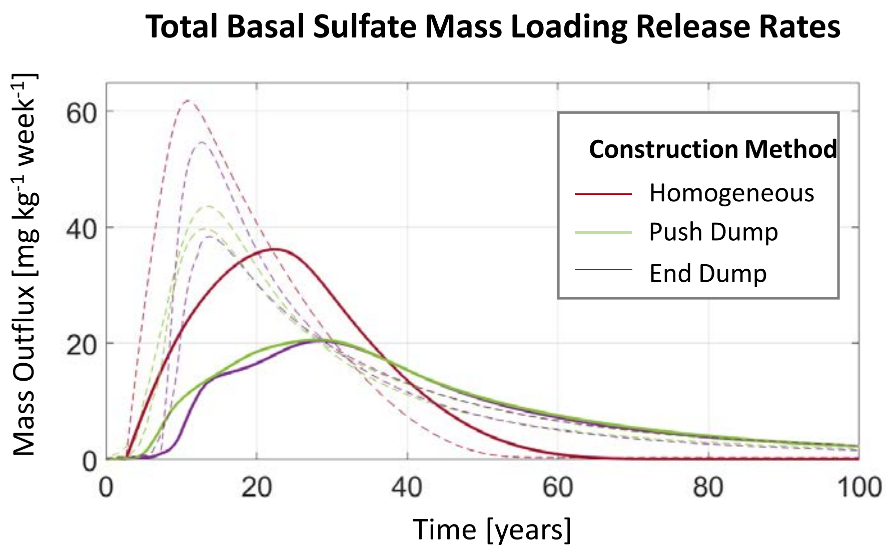


Influence of Structure Over Multiple Bench Models

Case		Max Mass Loading Rate [$mg^1\ kg^{-1}\ week^{-1}$]	Decrease from Homogeneous Case
Single Bench Models			
Homogeneous		61.8	-
Heterogeneous	Push Dump	43.6	29%
	End Dump	54.6	12%
Structure	Push Dump	39.8	36%
	End Dump	38.4	38%
Multiple Bench Models			
Homogeneous		**36.2**	**-**
Heterogeneous	Push Dump	**20.5**	**43%**
	End Dump	**20.6**	**43%**



0 Years



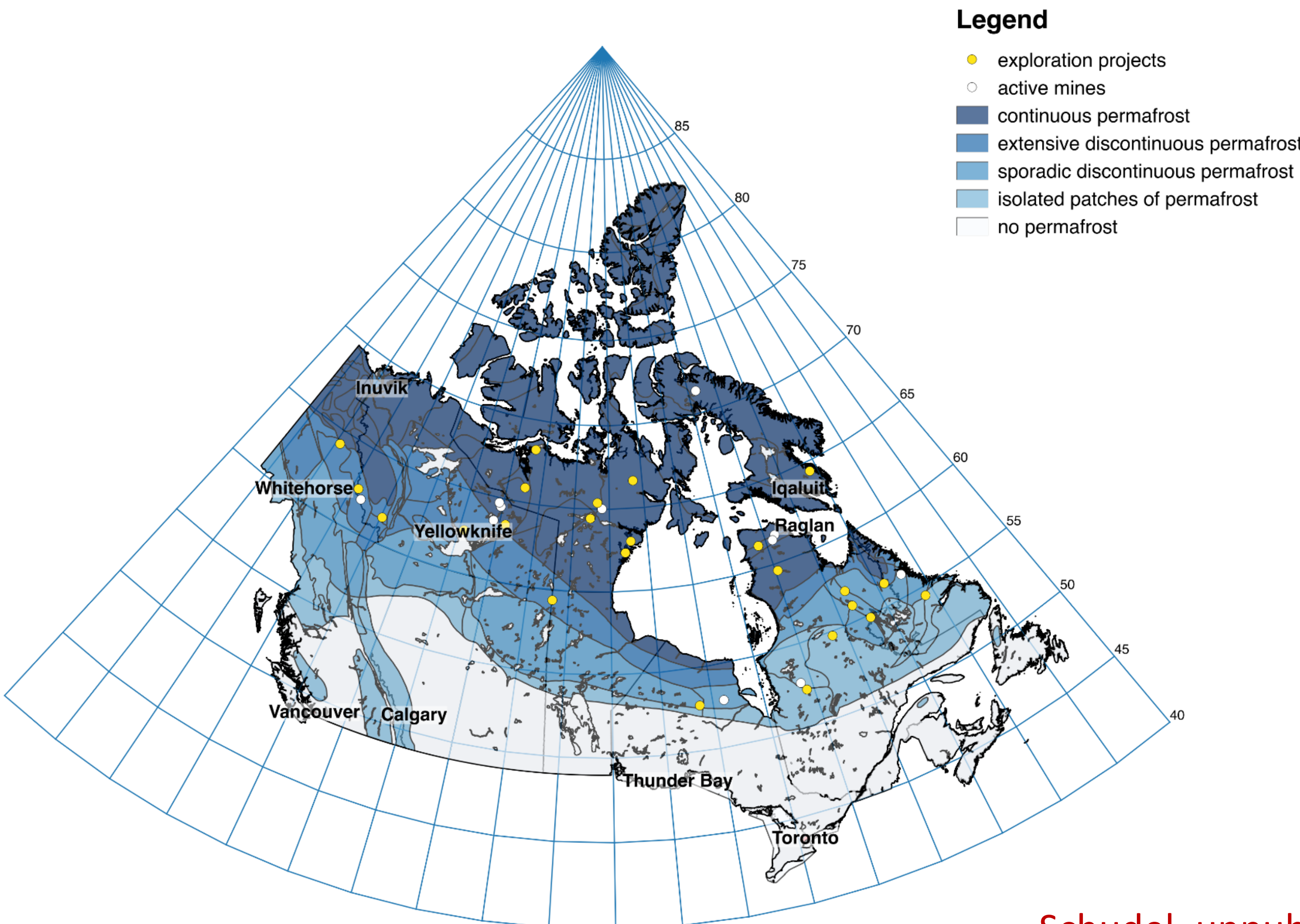
Lessons learned – construction methods

- **Inclusion** of **heterogeneity and construction methods** in RTM can have a **significant impact** on **predicted maximum mass loading rates** (reduced from homogeneous model by 36 – 43%)
- **Scale** and presence of **traffic surfaces** are **most important**
  - **Mass loading rates** were **comparable** by the **multi-lift** pile for **between construction methods** (push vs. end dumping)

RTM Examples Related to Waste Rock

- Case Study:
  - Diavik Waste Rock Research Project - reactive transport model (RTM) to identify scaling relationships for ARD from laboratory experiments to full-scale piles
- **Scenario Analyses**:
  - Effect of **internal structure**, **heterogeneity**, and **scale** on ARD release: ***Do pile construction methods affect ARD release, and if so, how?***
  - Effect of **climate change** on ARD generation and release **under cold climate conditions: In search for the tipping point.**

Permafrost and Mine Waste Storage Planning



Schudel, unpublished

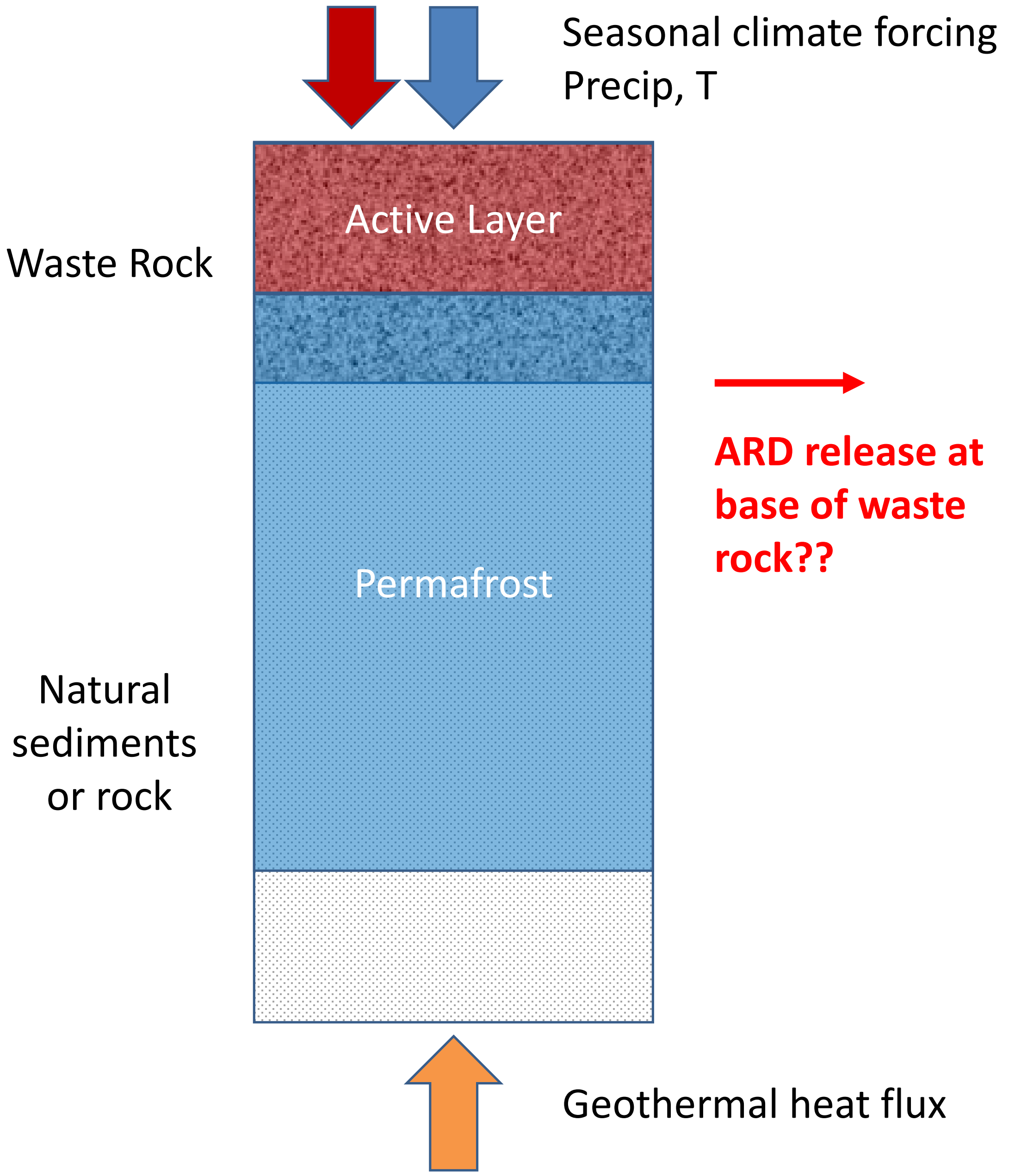
ARD generation and release under cold climate conditions, Xueying Yi, MSc student

Current work:

- Consider **heat** from **sulfide mineral oxidation**
- Capture effects of **freeze-thaw**
- **Insulation** from **snow cover**
- Influence of **TDS/solutes** on water **freezing-temperature**
- **Compare** differences in potential **mass loadings** under different **annual temperature changes** due to **climate change**

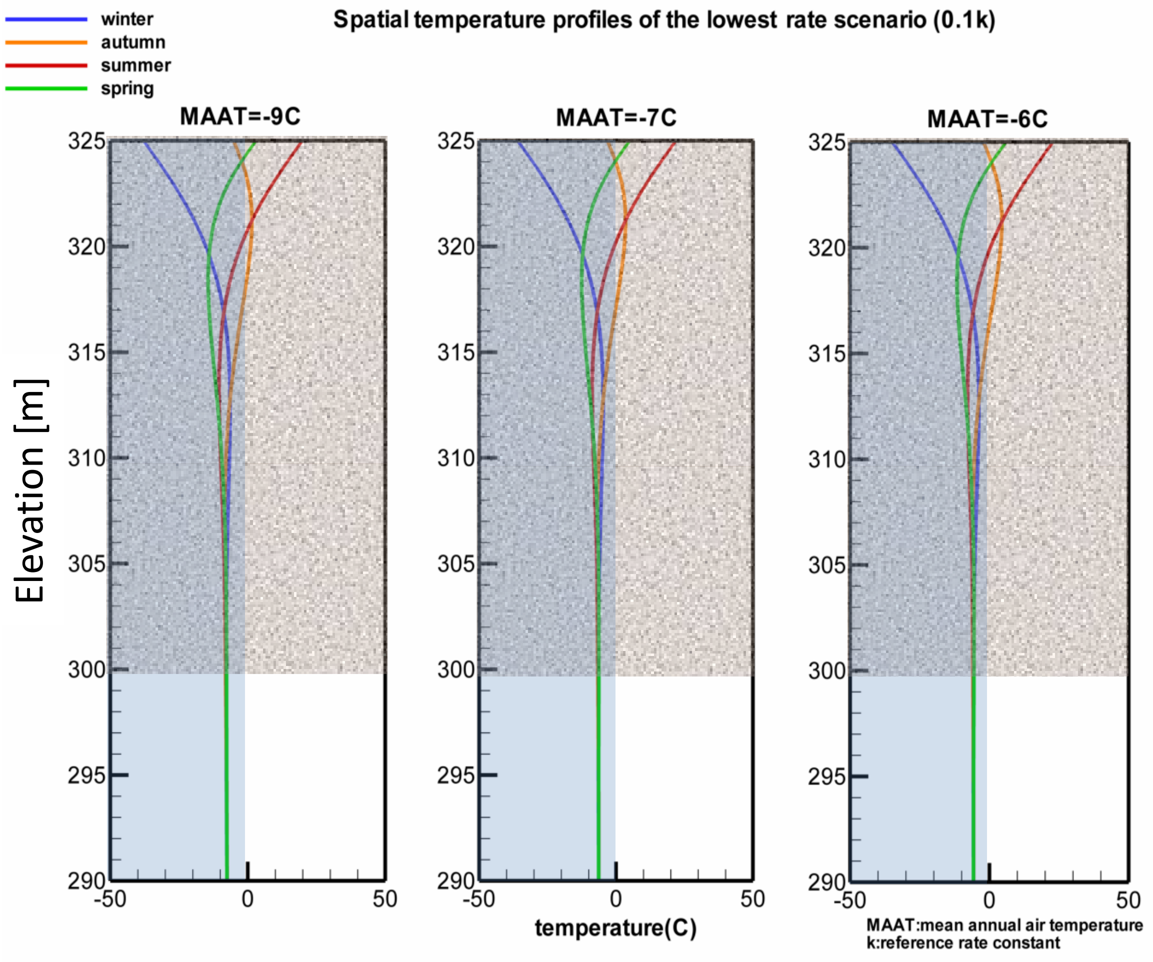
Conceptual Model

- Sulfide mineral oxidation in active layer
  - Seasonally controlled
  - Exothermic: generation of heat with effects on active layer and permafrost



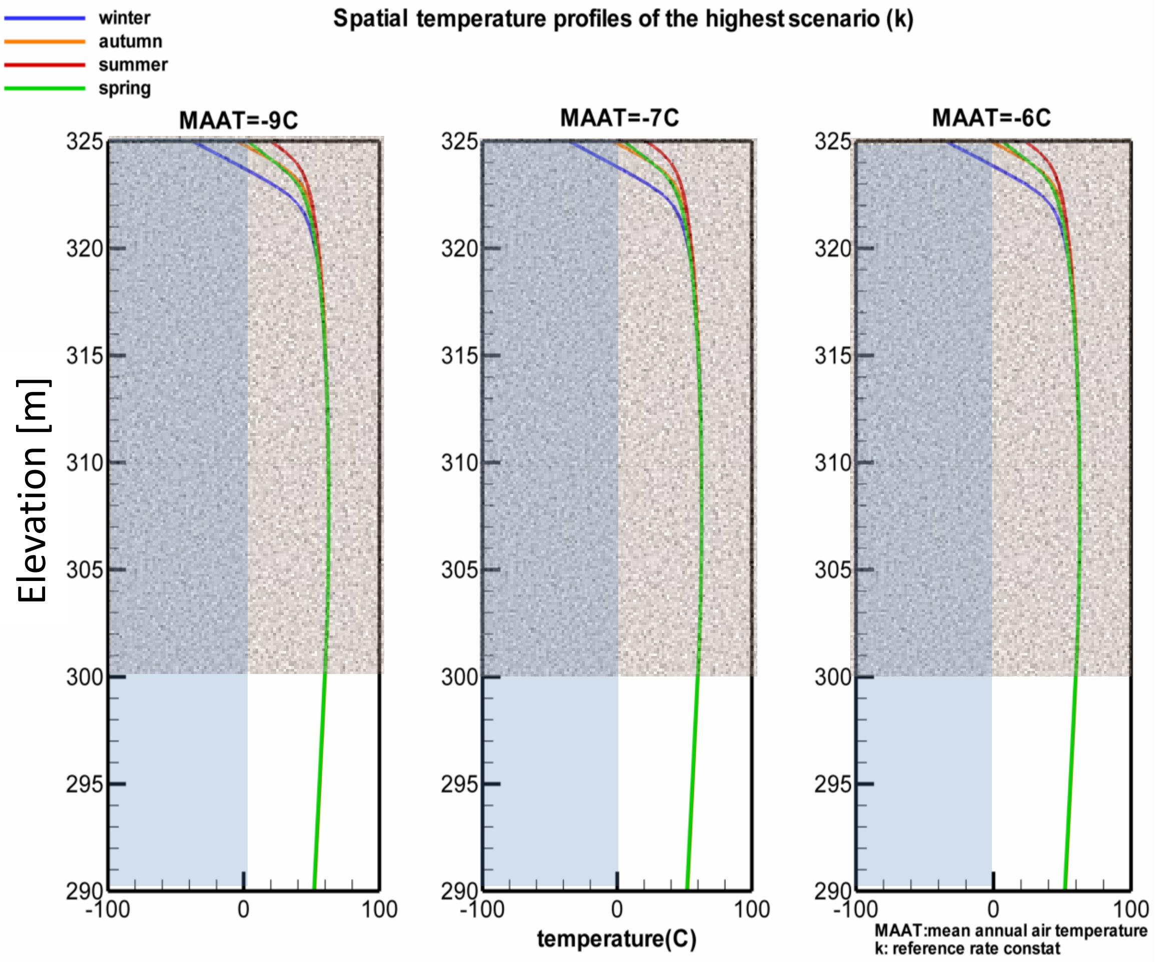
Simulated temperature profiles as a function of average yearly temperatures

- Pyrite oxidation rate at 25 deg C: 1.7×10^{-10} mol dm^{-3} bulk s^{-1}
- Minor differences in active layer thickness
- No ARD release in any of the cases



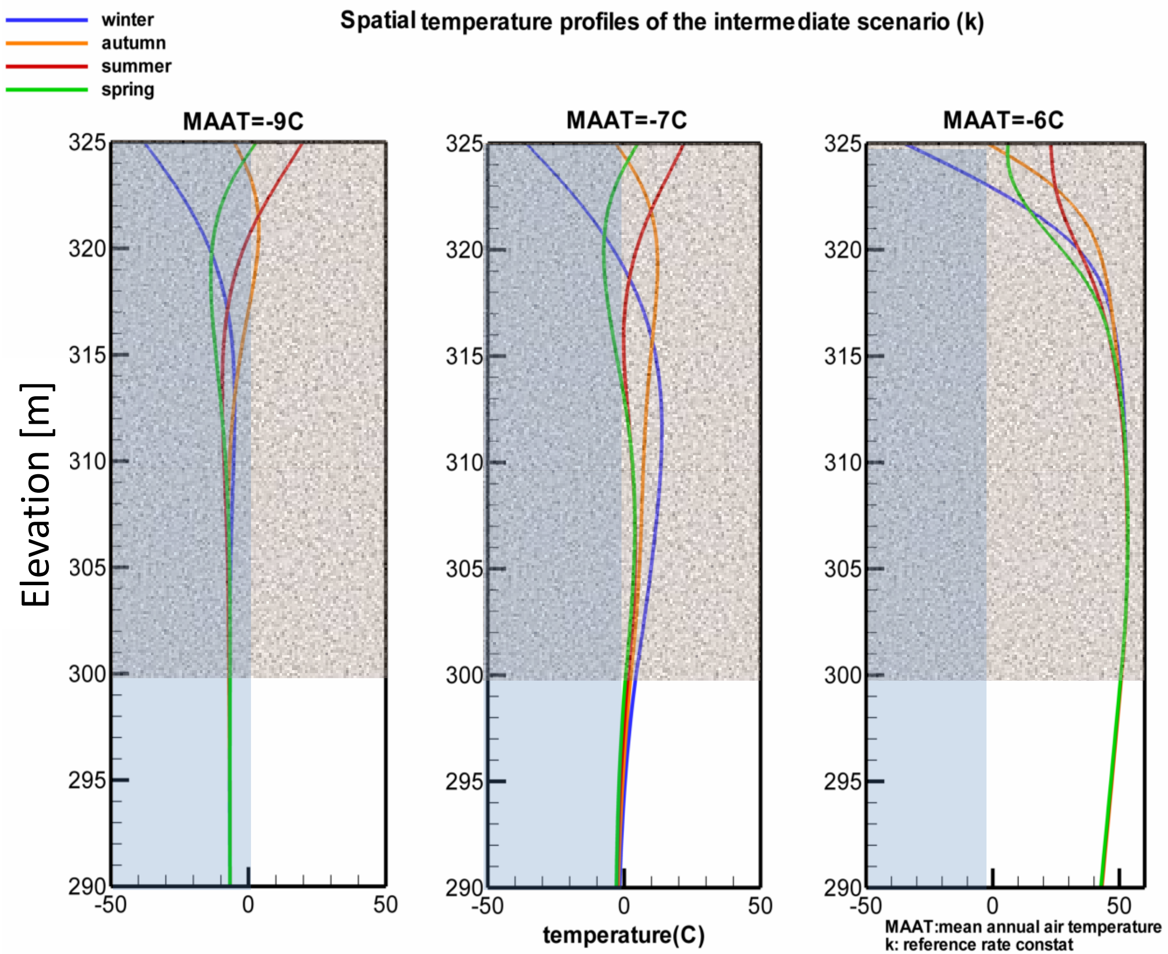
Simulated temperature profiles as a function of average yearly temperatures

- Pyrite oxidation rate at 25 deg C: 1.7×10^{-8} mol dm^{-3} bulk s^{-1}
- Active layer reaches below based of WRP in all cases
- ARD release in all cases

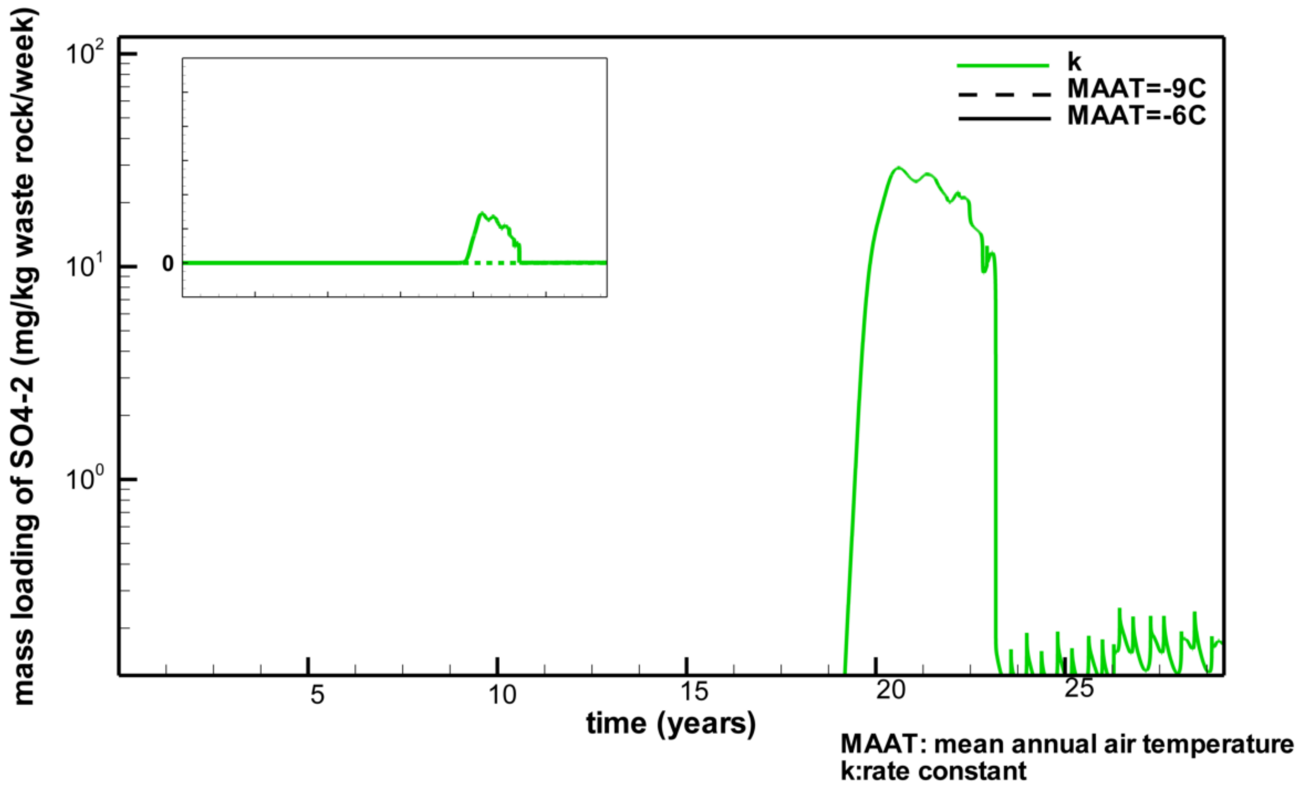


Simulated temperature profiles as a function of average yearly temperatures

- Pyrite oxidation rate at 25 deg C: 1.7 x 10^{-9} mol dm^{-3} bulk s^{-1}
- Tipping Point!!
- ARD release due to increased MAAT



Basal sulfate loading of intermediate scenario over time with MAAT = -9 deg C and -6 deg C



Lessons learned – cold climate conditions and climate change

- Just starting to learn
- Preliminary simulation results suggest that climate change will have a limited effect in many cases
- On the other hand, effect can be substantial, if tipping point is reached
- Increase of active layer thickness to base of WRP may lead to short-lived high mass loadings. Food for thought.

Where do we go from here?

- Reactive transport models for simulating processes in mine tailings and waste rock are available
- MIN3P: 20+ year development and ongoing
- Complex geometry can now be included
- Computational efficiency allows to carry our larger scale 2D simulations, if needed
- Looking towards expanding model capabilities for non-isothermal, multiphase systems

Is there interest in the ARD community to use RTM models? If so, what are you looking for?

Reactive Transport Modeling Interest Survey

https://tinyurl.com/v5bw5dl

…or grab a paper survey at reception table!

References

1. Anterrieu O., Chouteau M., & Aubertin M. (2010). Geophysical characterization of the large-scale internal structure of a waste rock pile from a hard rock mine. *Bulletin of engineering geology and the environment*, *69*(4), 533-548.
2. Everett D., Pearce P. (2016). Principal mineral areas, producing mines, and oil and gas elds in canada. URL: http://www:nrcan:gc:ca/mining-materials/publications/8790.
3. Hawley M., & Cunning, J. (2017). *Guidelines for Mine Waste Dump and Stockpile Design*. CSIRO Publishing.
4. Mayer K.U., Frind E.O., Blowes D.W. (2002). Multicomponent reactive transport modeling in variably saturated porous media using a generalized formulation for kinetically controlled reactions. Water Resources Research, 38(9), 13-1-21.
5. Natural Resources Canada (2000). Canadian Permafrost, Geological Survey of Canada. Free Data - GeoGratis. URL: http://geogratis:gc:ca/api/en/nrcan-rncan/ess-sst/092b663d-198b-5c8d-9665-fa3f5970a14f.
6. Natural Resources Canada (2015). Map of Top 100 Exploration and Deposit Appraisal Projects of 2015 (Based on Expenditures). URL: http://www:nrcan:gc:ca/miningmaterials/exploration/17179
7. Raymond K. (unpublished). Numerical Modeling of Mass Loadings from Waste Rock Piles Affected by Heterogeneity and Structure. Master's thesis, University of British Columbia.
8. Schippers, A., Sand, W. (1999). Bacterial leaching of metal sulfides proceeds by two indirect mechanisms via thiosulfate or via polysulfides and sulfur. Appl. Environ. Microbiol. 65(1), 319-321.
9. Schudel G., Plante B., Bussière B., McBeth J., Dufour G. (2019). The effect of temperature and salinity on the geochemical behavior of sulfidic tailings. In: The 26th British Columbia MEND Metal Leaching/Acid Rock Drainage Workshop. Vancouver, Canada, 4-5 December 2019
10. Statistics Canada (2016). Boundary Files, 2016 Census. URL: http://www12:statcan:gc:ca/census-recensement/2011/geo/bound-limit/bound-limit-2016-eng:cfm.
11. Wilson D, Amos RT, Blowes DW, Langman JB, Ptacek CJ, Smith JL, Sego DC (2018) Diavik waste rock project: A conceptual model for temperature and sulfide-content dependent geochemical evolution of waste rock – Laboratory scale. Appl Geochem. 89:160-172
12. Wilson D, Amos RT, Blowes DW, Langman JB, Ptacek CJ, Smith JL, Sego DC (2018) Diavik Waste Rock Project: Scale-up of a reactive transport model for temperature and sulfide-content dependent geochemical evolution of waste rock. Appl Geochem. 96:177-190
13. Yi X. (unpublished). Development and application of THC modeling capabilities for assessment of cover performance and mine waste weathering in Northern climates. Master's thesis, University of British Columbia.

Conceptual Model – Theory

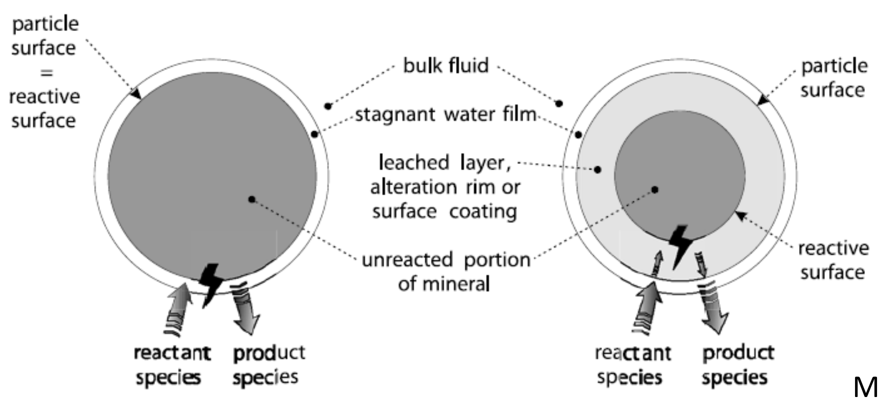
Oxidation by $O_{2(aq)}$:

$$Fe_{0.852}Ni_{0.004}Co_{0.001}S + 1.9285O_{2(aq)} + 0.143H_2O \rightarrow$$
$$0.852Fe^{2+} + 0.004Ni^{2+} + 0.001Co^{2+} + SO_4^{2-} + 0.286H^+$$

Oxidation by Fe^{3+}:

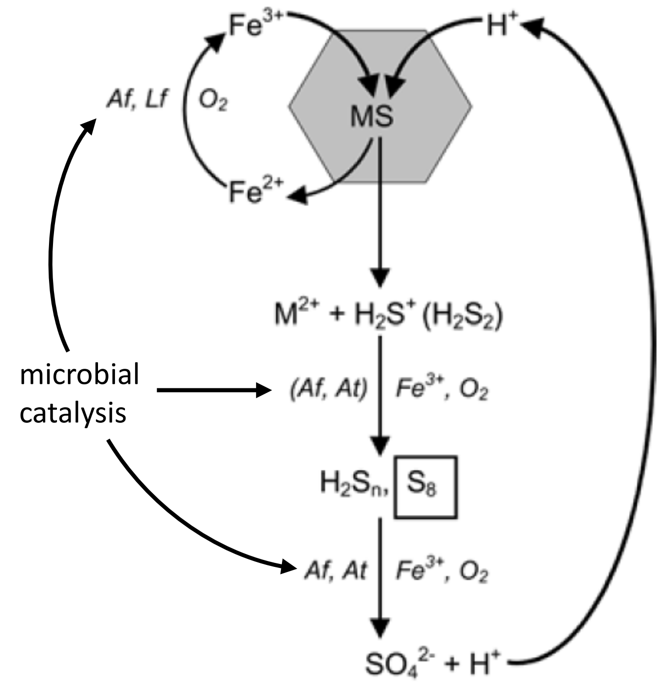
$$Fe^{2+} + 0.25O_{2(aq)} + H^+ \rightarrow \mathrm{Fe}^{3+} + 0.5H_2O$$
$$Fe_{0.852}Ni_{0.004}Co_{0.001}S + 1.714Fe^{3+} \rightarrow$$
$$2.566Fe^{2+} + 0.004Ni^{2+} + 0.001Co^{2+} + S^0$$
$$S^0 + 1.5O_{2(aq)} + H_2O \rightarrow SO_4^{2-} + 2H^+$$

Sulfide oxidation simulated using shrinking core model



Mayer et al., 2002

polysulfide mechanism of sulfide mineral oxidation



Schippers and Sand, 1999