Investigation of waste rock weathering and drainage:

a multiscale field study at the Antamina Mine, Peru

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BC MEND ML/ARD 2020

A long-term, multi-scale research program

The Antamina mine, Peru:

High elevation: 4300 masl

Alpine climate with bimodal precipitation

Complex Cu-Zn skarn deposit

Mostly circumneutral pH drainage

Elements of concern: As, Cu, Zn and Mo

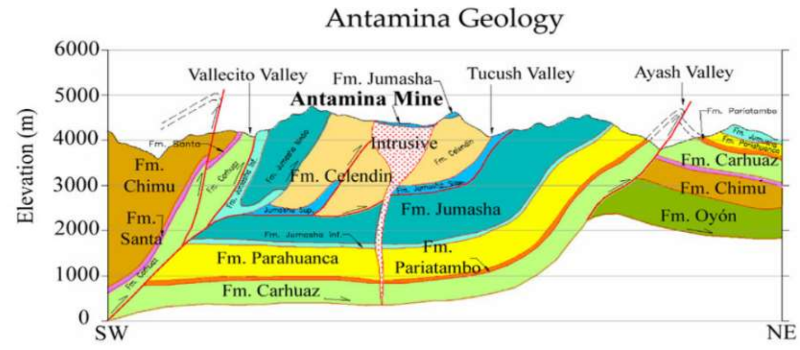


Figure 1.2 – Cross section of the geology at Antamina (modified from Lipten, 2003)

One of the largest Cu mines in the world!

Project goals

Provide Antamina a knowledge base to support waste-rock management and decision making:

- Operational criteria
- Closure planning

Strategy

Large-scale pile experiments – most closely mimic field conditions but are costly, slow.

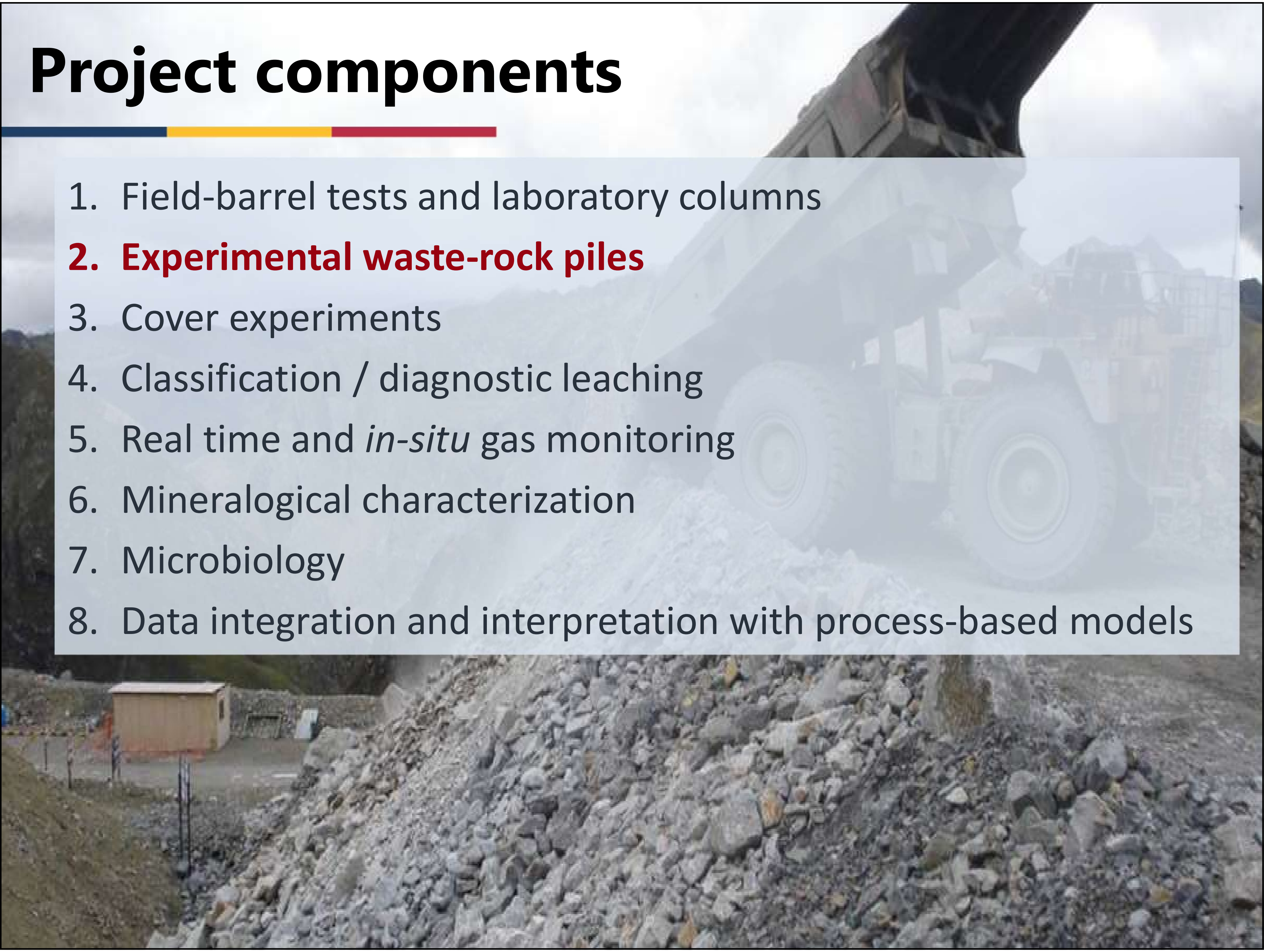
↕

Mechanistic understanding

↕

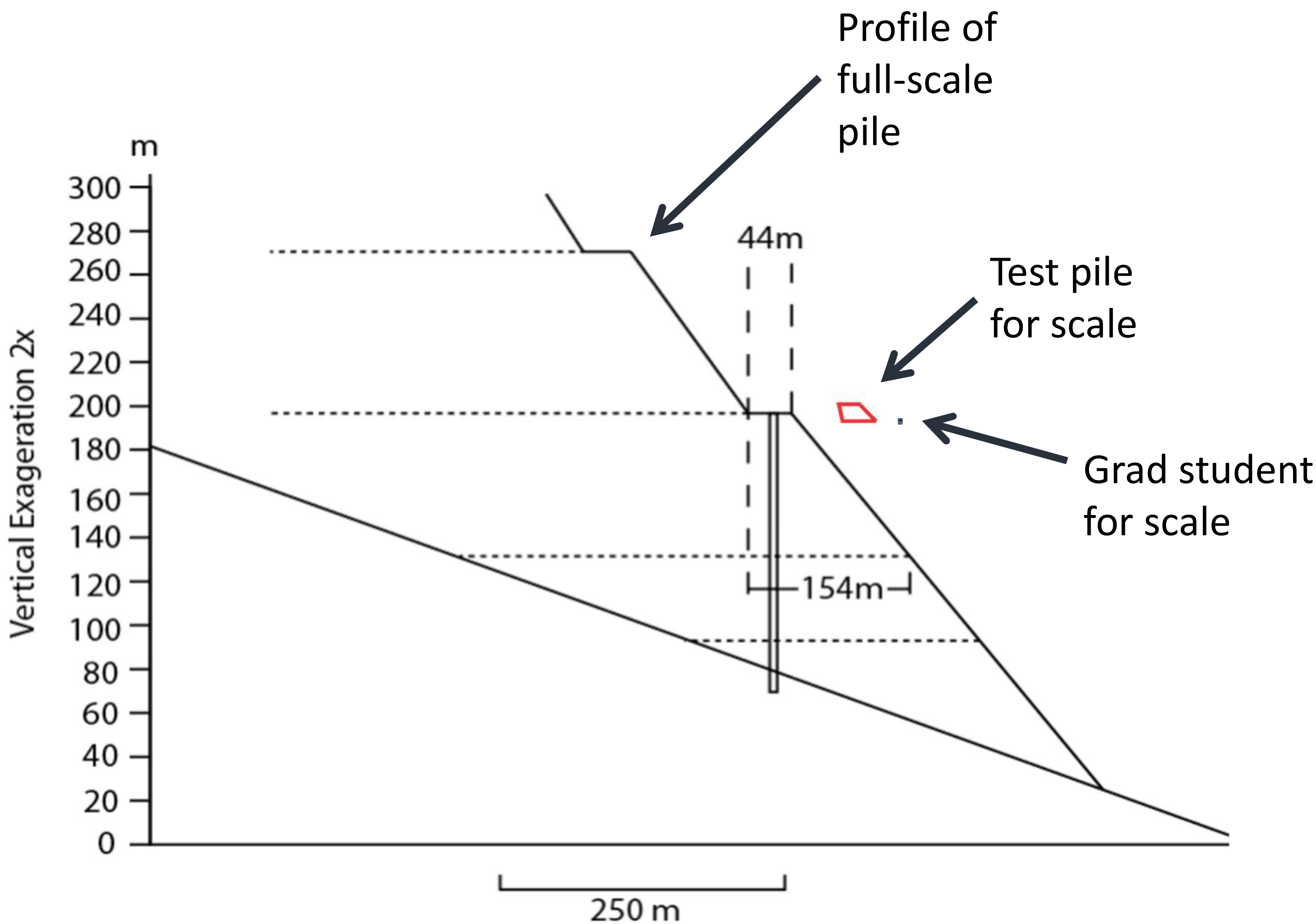
Smaller-scale experiments – poorly represent field conditions but are relatively inexpensive, rapid and may be used in diagnostic sense for operational decision making

Project components



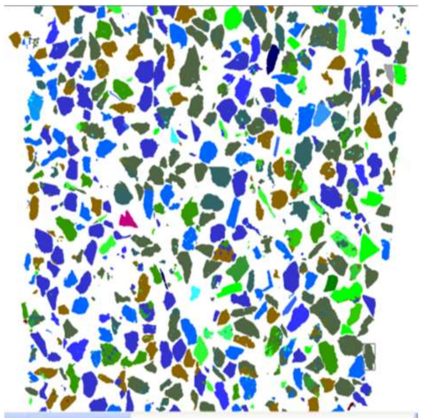
1. Field-barrel tests and laboratory columns
2. **Experimental waste-rock piles**
3. Cover experiments
4. Classification / diagnostic leaching
5. Real time and *in-situ* gas monitoring
6. Mineralogical characterization
7. Microbiology
8. Data integration and interpretation with process-based models

Scaling-up weathering/drainage processes



Vriens et al., 2020, Journal of Contaminant Hydrology

Integration with mechanistic models



$$\phi_f R_f \frac{\partial c_f}{\partial t} = \nabla \cdot (\mathbf{D}_f \cdot \nabla c_f) - \mathbf{q} \cdot \nabla c_f - F_m$$

$$\frac{\partial \theta_w}{\partial t} = \nabla \cdot \left[K(\psi) \left(\nabla \psi + \nabla z \right) \right],$$

$$\theta_w = \theta_w(\psi).$$

MIN3P + gas + heat

Vriens et al., 2020, Journal of Contaminant Hydrology

Seigneur et al., 2021, Journal of Contaminant Hydrology

Research team

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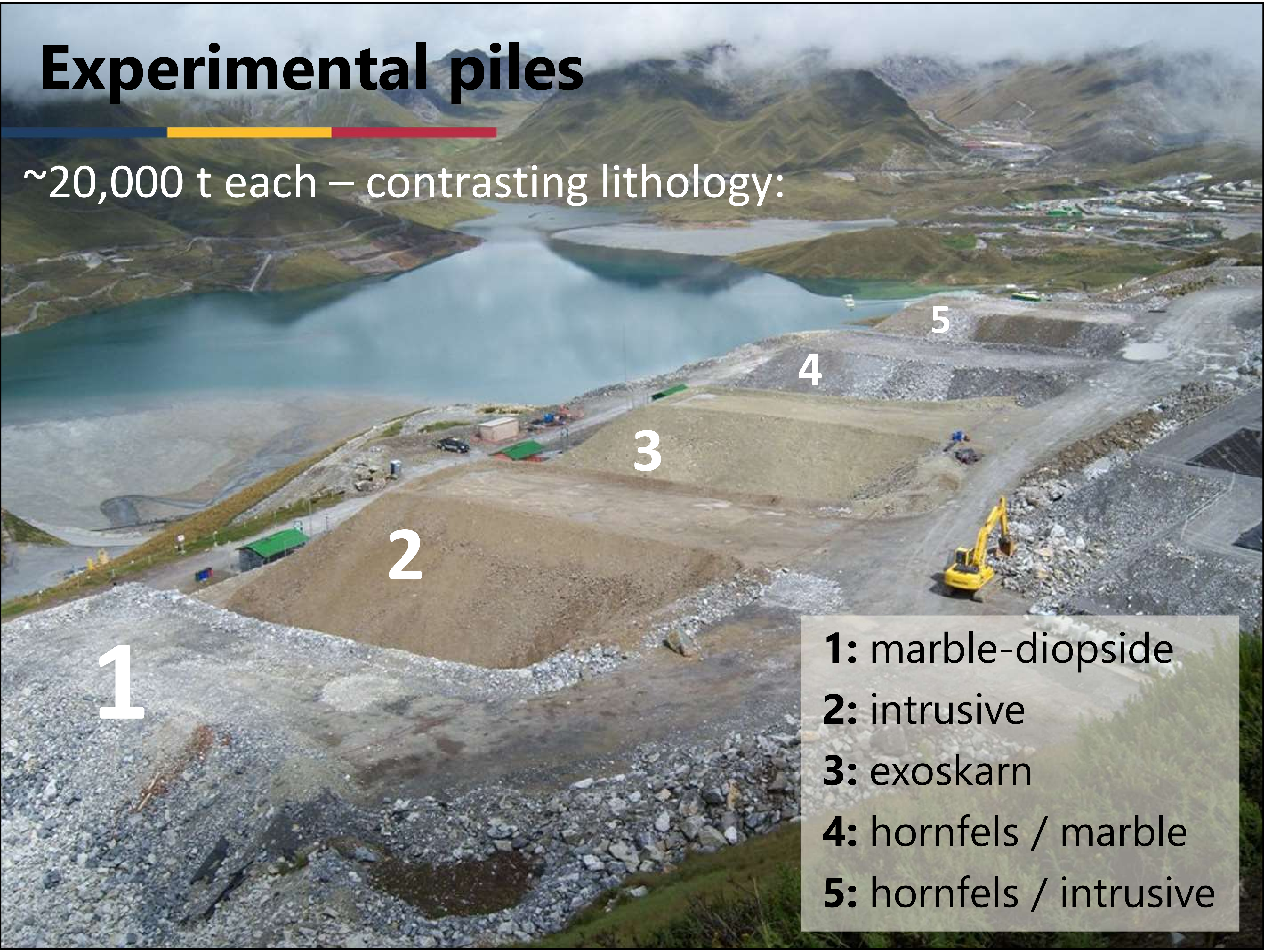
Experimental piles

~20,000 t each – contrasting lithology:



1: marble-diopside

2: intrusive

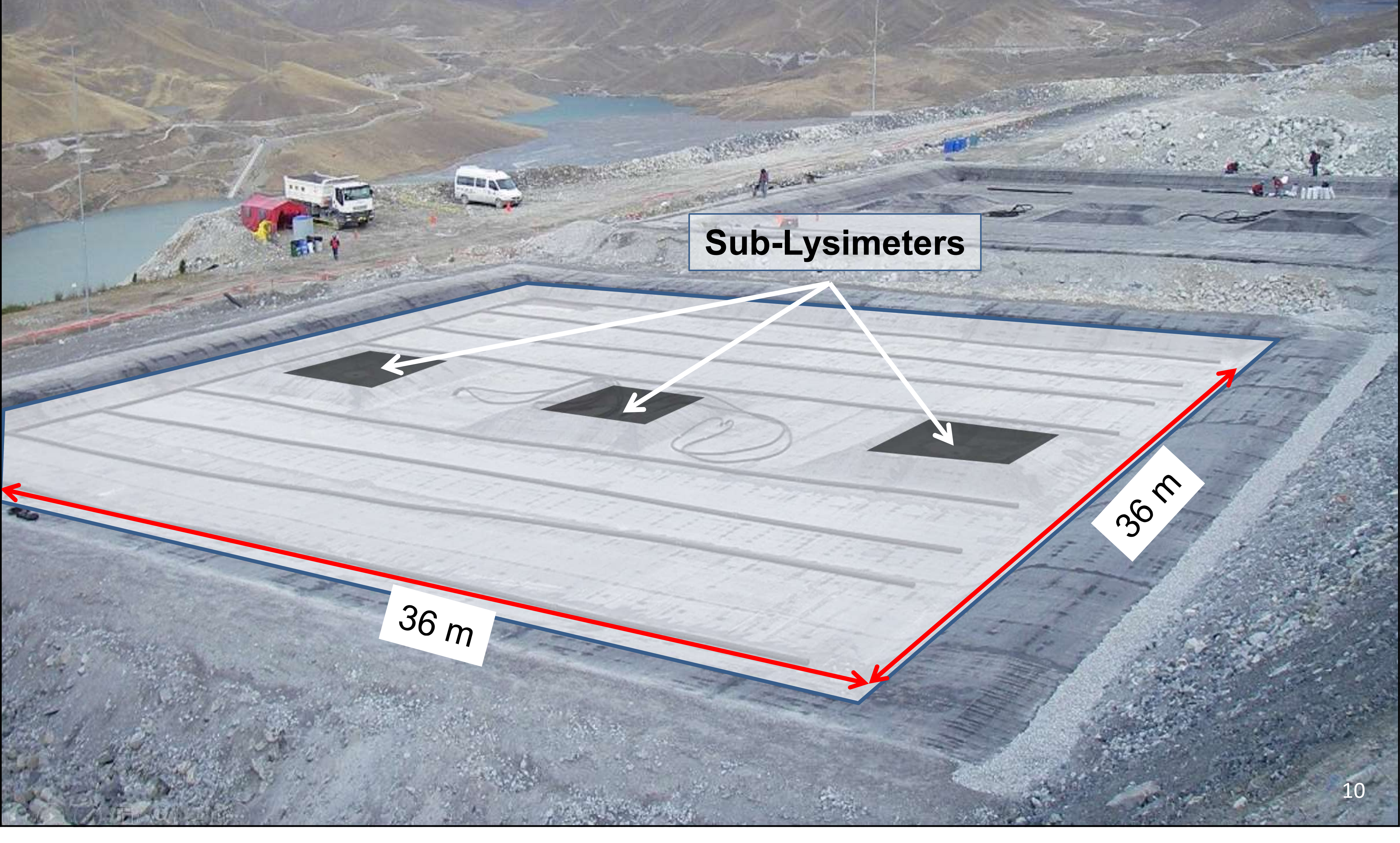
3: exoskarn

4: hornfels / marble

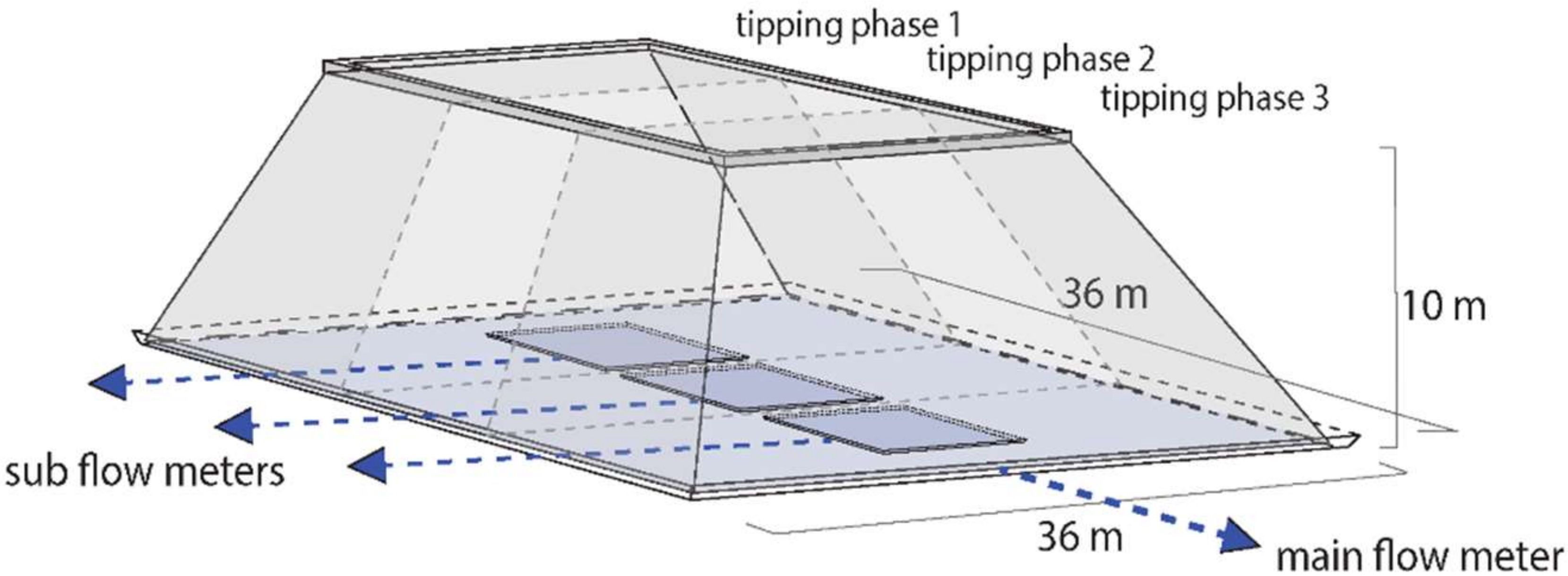
5: hornfels / intrusive

Experimental piles

Protective cover and sublysimeters



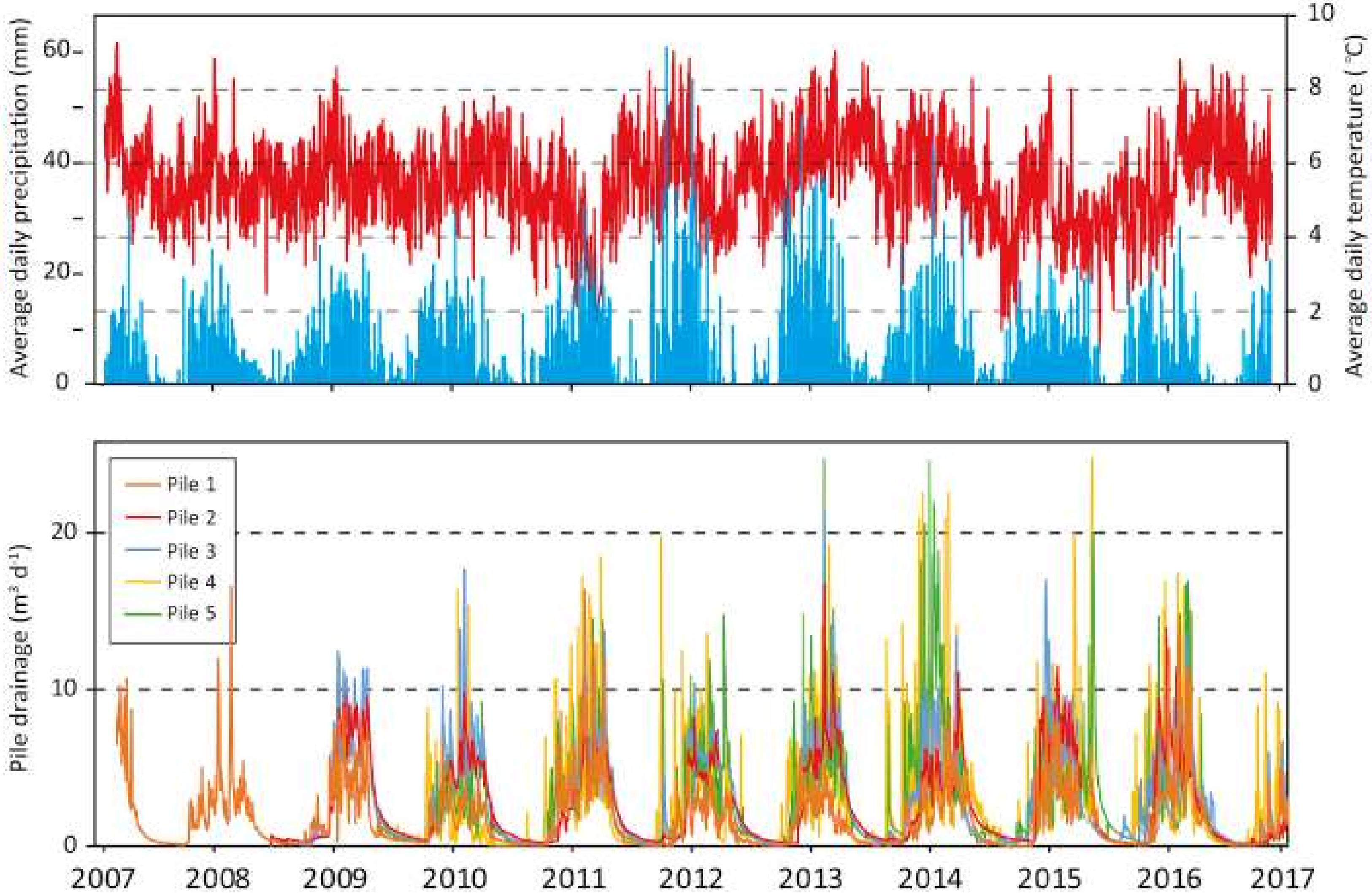
Experimental piles: schematic



Vriens et al., 2019, Chemosphere

Long-term drainage dynamics

Seasonal fluctuations due to hydrological transport…



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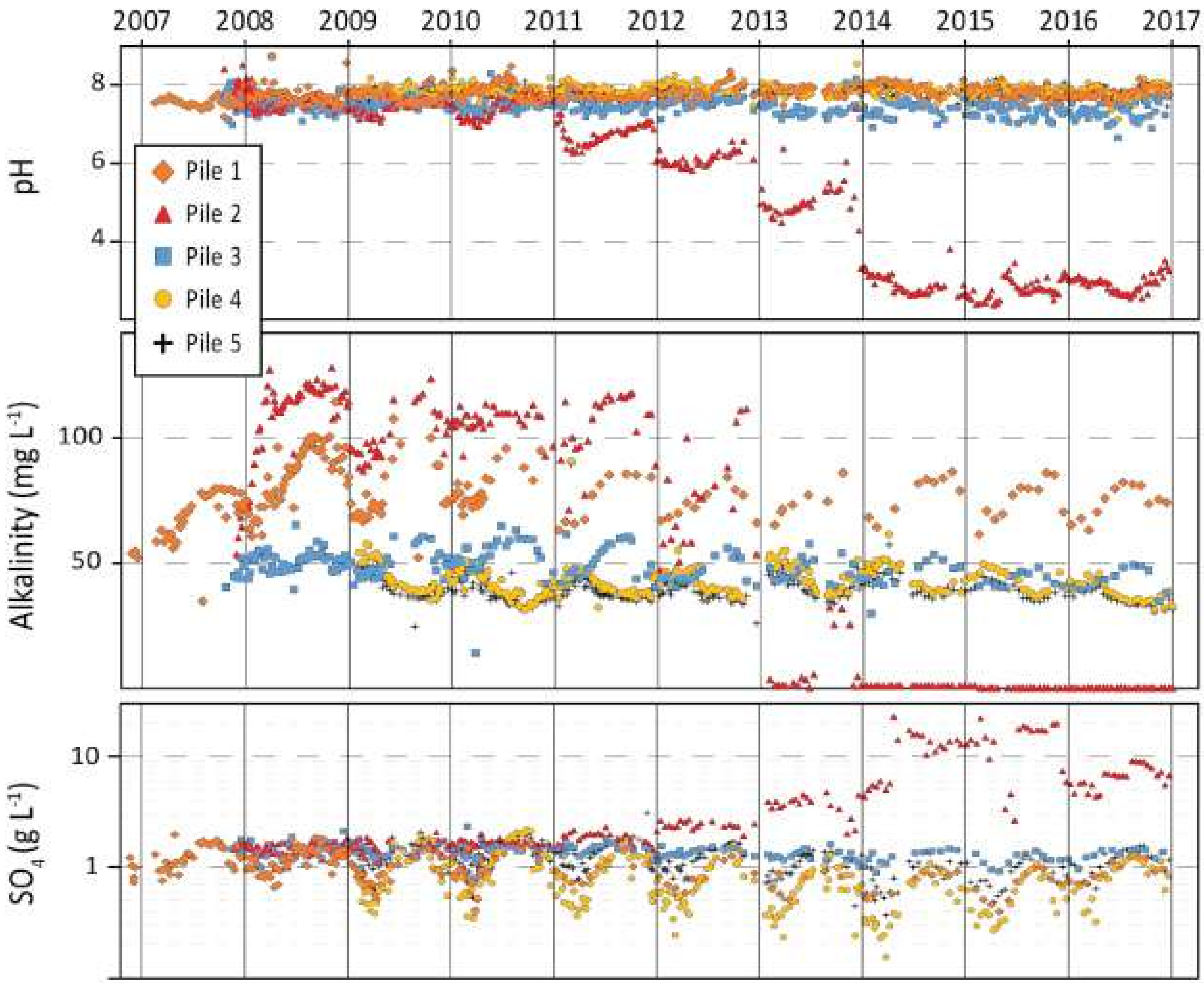
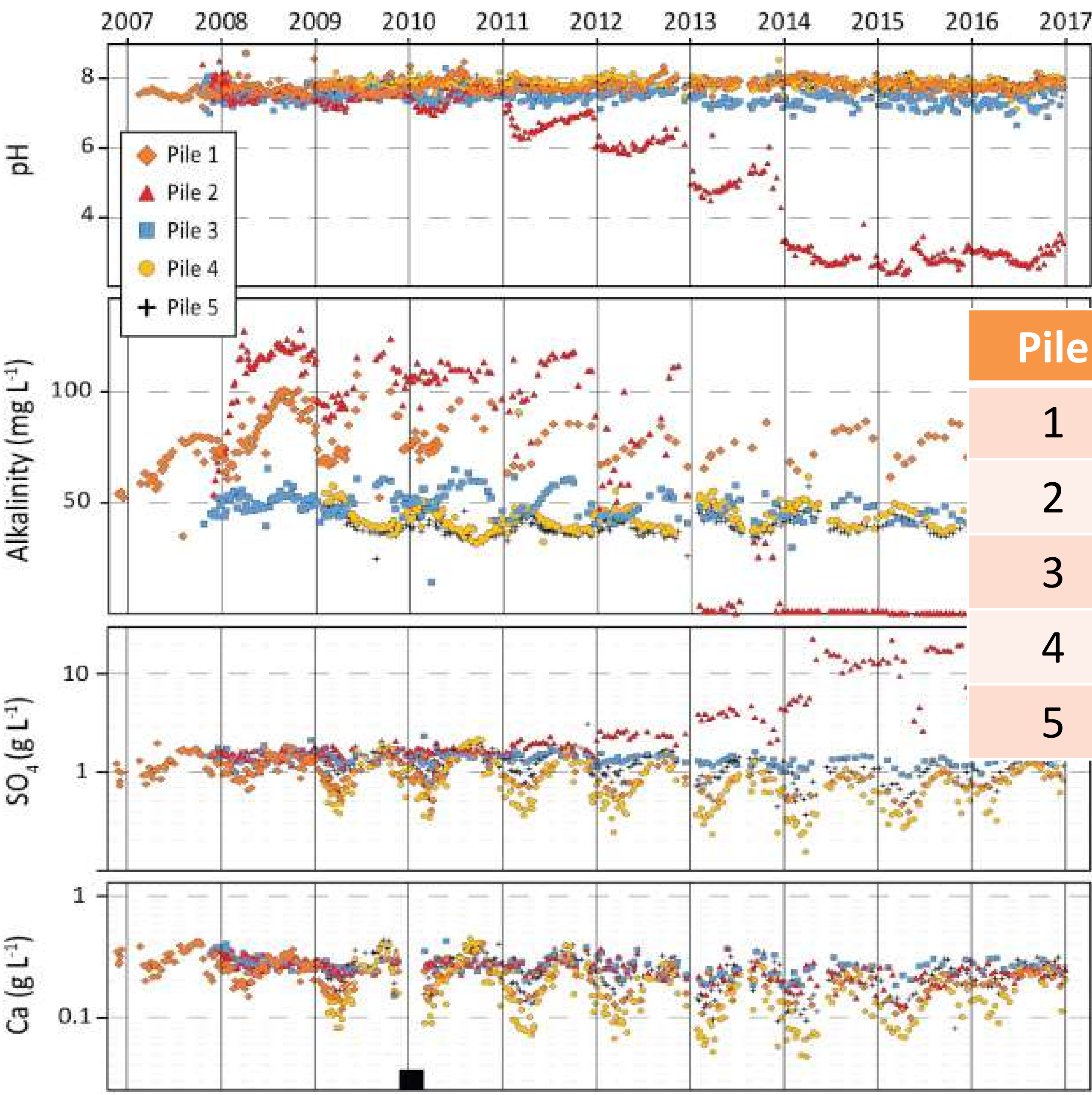
Experimental pile drainage dynamics



Short-term oscillations versus long-term trends in drainage chemistry

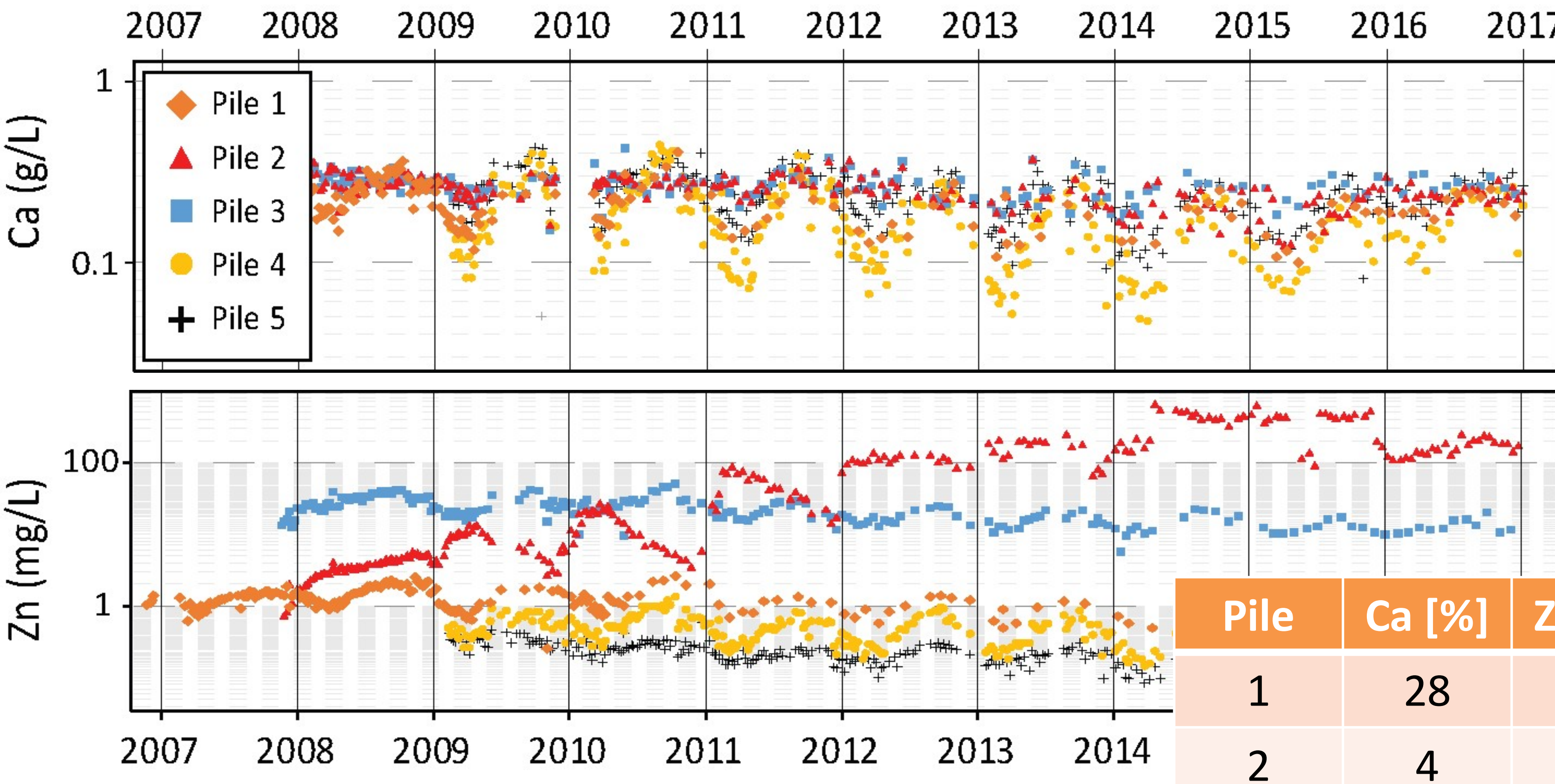
Vriens et al., 2019, Chemosphere

Experimental pile drainage dynamics



Pile	NP/AP	% S
1	38	0.5
2	0.3	2.6
3	5.2	3.8
4	35	0.5
5	28	0.6

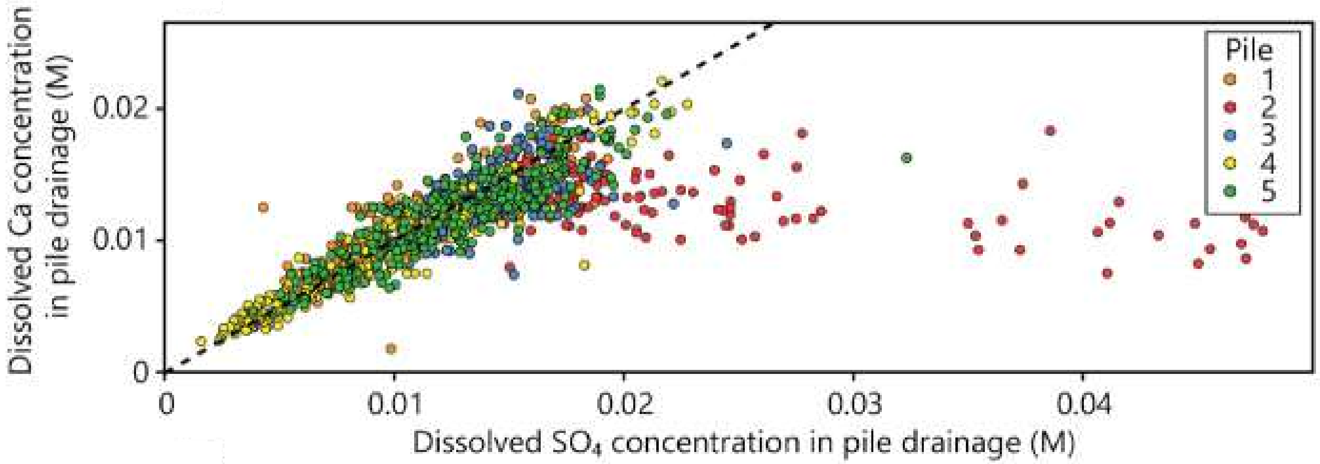
Experimental pile drainage dynamics

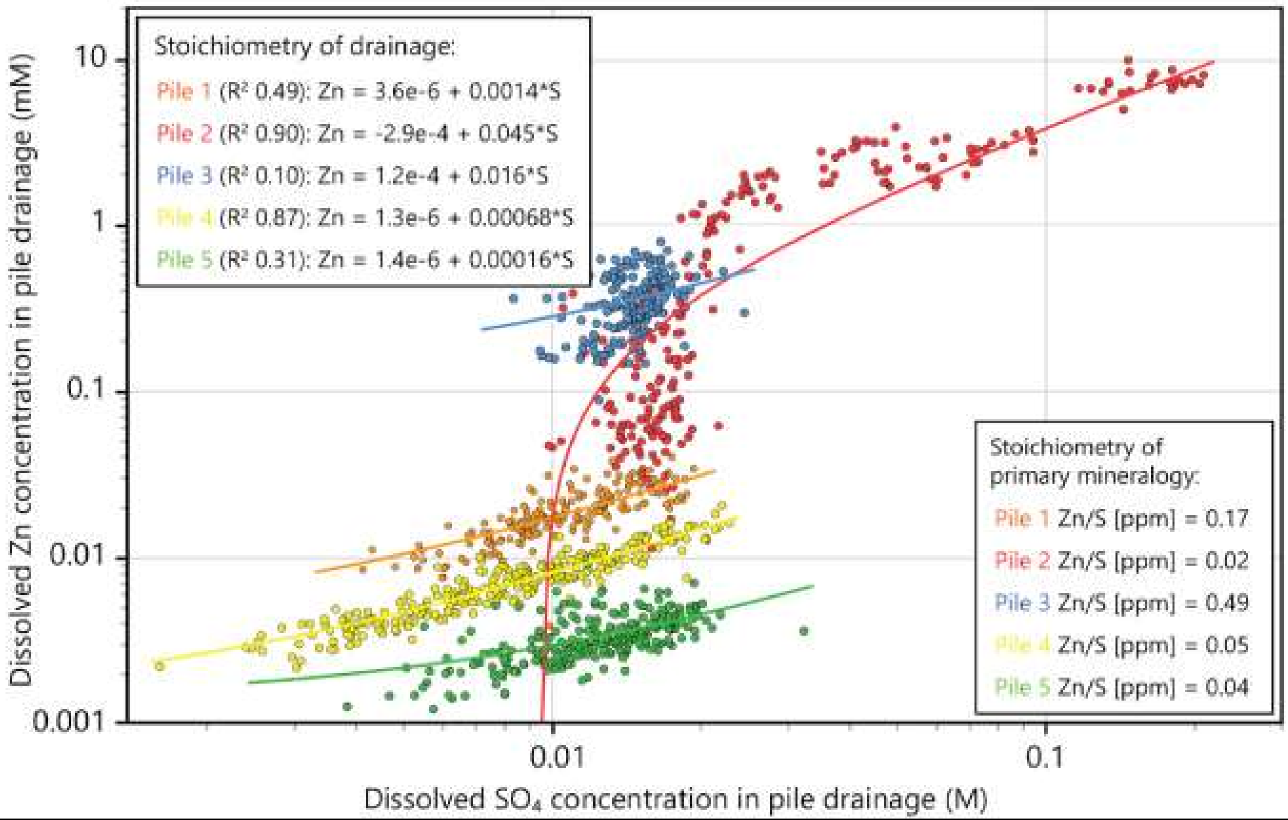


Pile	Ca [%]	Zn [%]
1	28	318
2	4	198
3	11	19,120
4	32	356
5	26	341

Vriens et al., 2019, Chemosphere

Experimental pile drainage dynamics





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Decoupling of mineralogy and drainage

1. Weathering rates and acidification largely expected based on primary waste rock mineralogy
2. Strong and selective retention of metals (>99%) in experimental piles, unexplained loading *spikes*

- Physical waste-rock properties (i.e., PSD)
- Sorption
- Secondary mineral precipitation
- Mineral passivation or occlusion
- Preferential drainage flow
- Basal mixing

Vriens et al., 2019, Chemosphere

Secondary mineral formation

1. Equilibrium modeling
2. Raman spectroscopy
3. Quantitative XRD

Vriens et al., 2019, Chemosphere

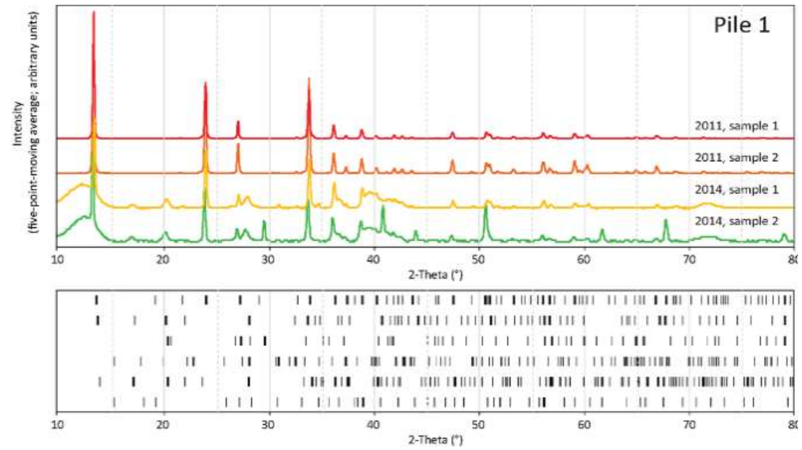
Secondary mineral assemblage

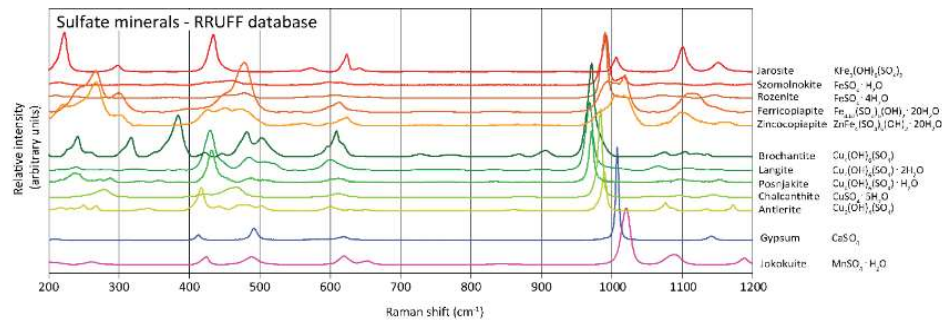
<u>Gypsum ($CaSO_4$):</u>
up to 95%!

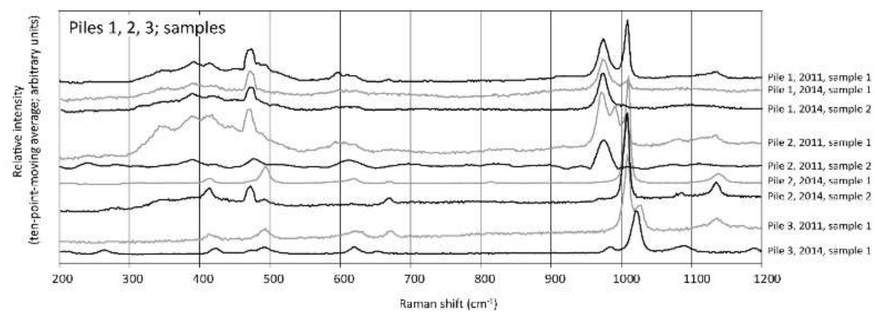
<u>Fe-oxyhydroxides and –sulfates (>10%):</u>
Ferrihydrite, goethite, lepidocrocite, jarosite, melanterite

<u>Cu/Zn-hydroxysulfates (<5%):</u>
brochantite [$Cu_4SO_4(OH)_6$]
chalcanthite [$CuSO_4{\cdot}5H_2O$]

<u>Cu/Zn-hydroxycarbonates (<5%):</u>
aurichalcite [$(Zn,Cu)_5(CO_3)_2(OH)_6$]
malachite [$Cu_2CO_3(OH)_2$]





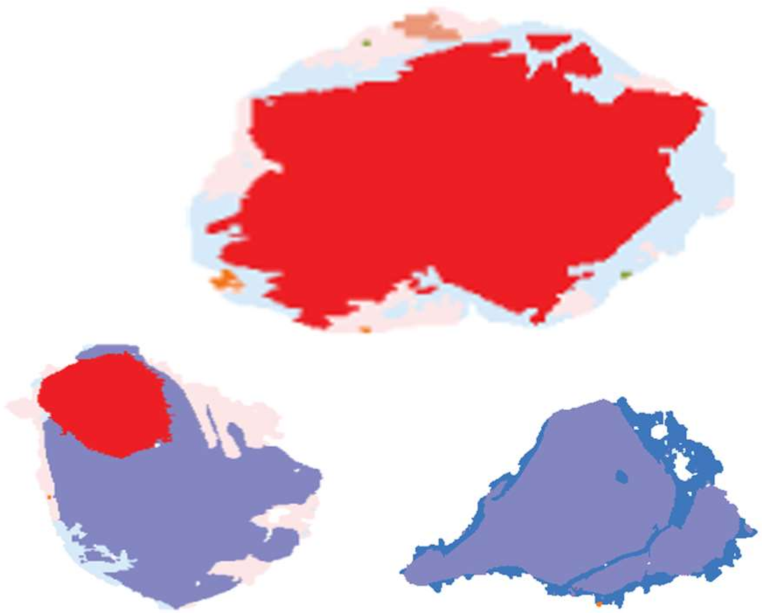


<u>Vriens</u> et al., 2019, Chemosphere

Effects of secondary minerals

Challenging quantification of amorphous phases with XRD:

→ Quantitative automated mineralogy



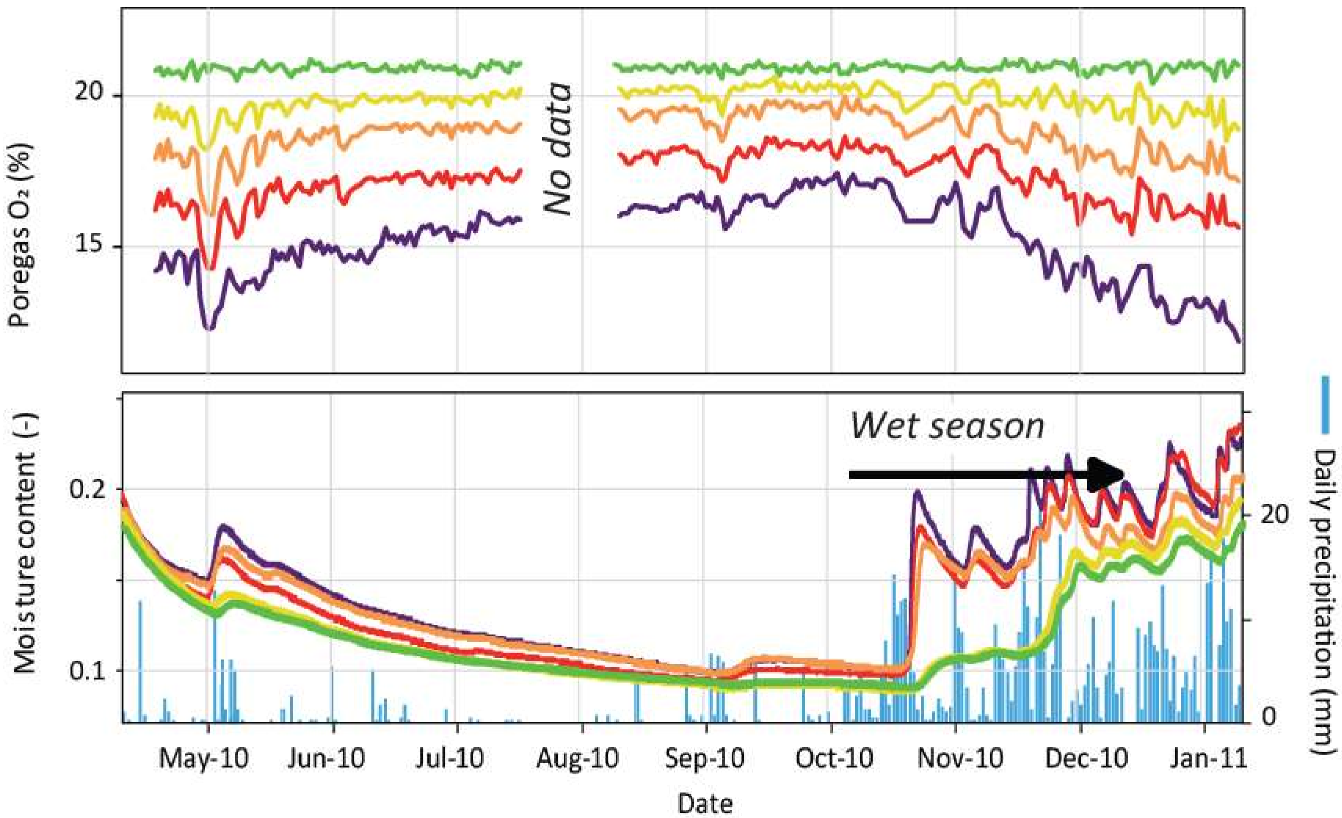
Effects:

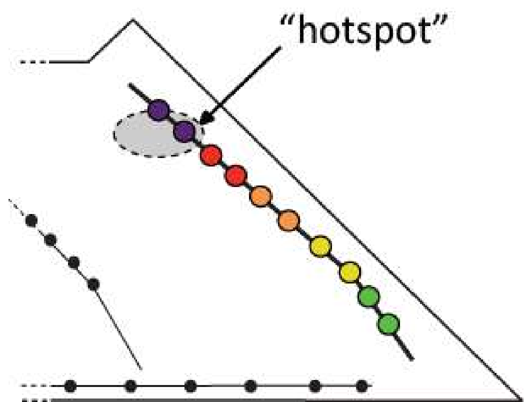
- *Temporary* internal retention of metals/solutes → weathering rates?
- Occlusion of reactive surface area: *Passivation*
  → adjustment of 'reactivity'
- Hydromechanical feedbacks: pore widening/clogging
  → geotechnical properties?
- Peak mobilization under drainage chemical (redox) gradients

Vriens et al., 2019, Chemosphere
St-Arnault et al., 2020, Minerals Engineering
St-Arnault et al., 2019, Applied Geochemistry

Variable secondary mineral stability

… under different geochemical conditions





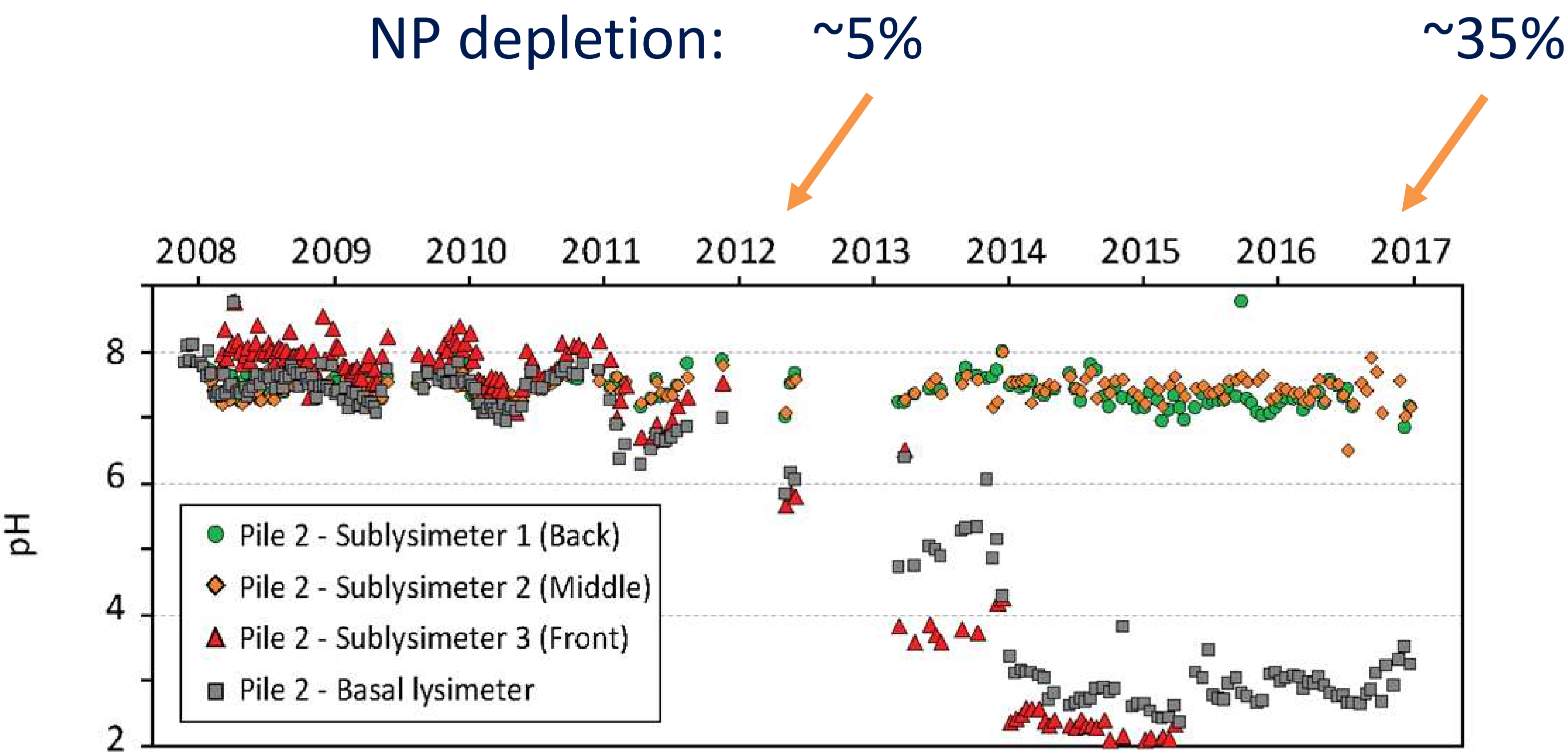
→ As a function of waste rock composition and drainage chemistry

→ As a function of prevailing *in-situ* redox conditions

Vriens et al., 2019, Applied Geochemistry

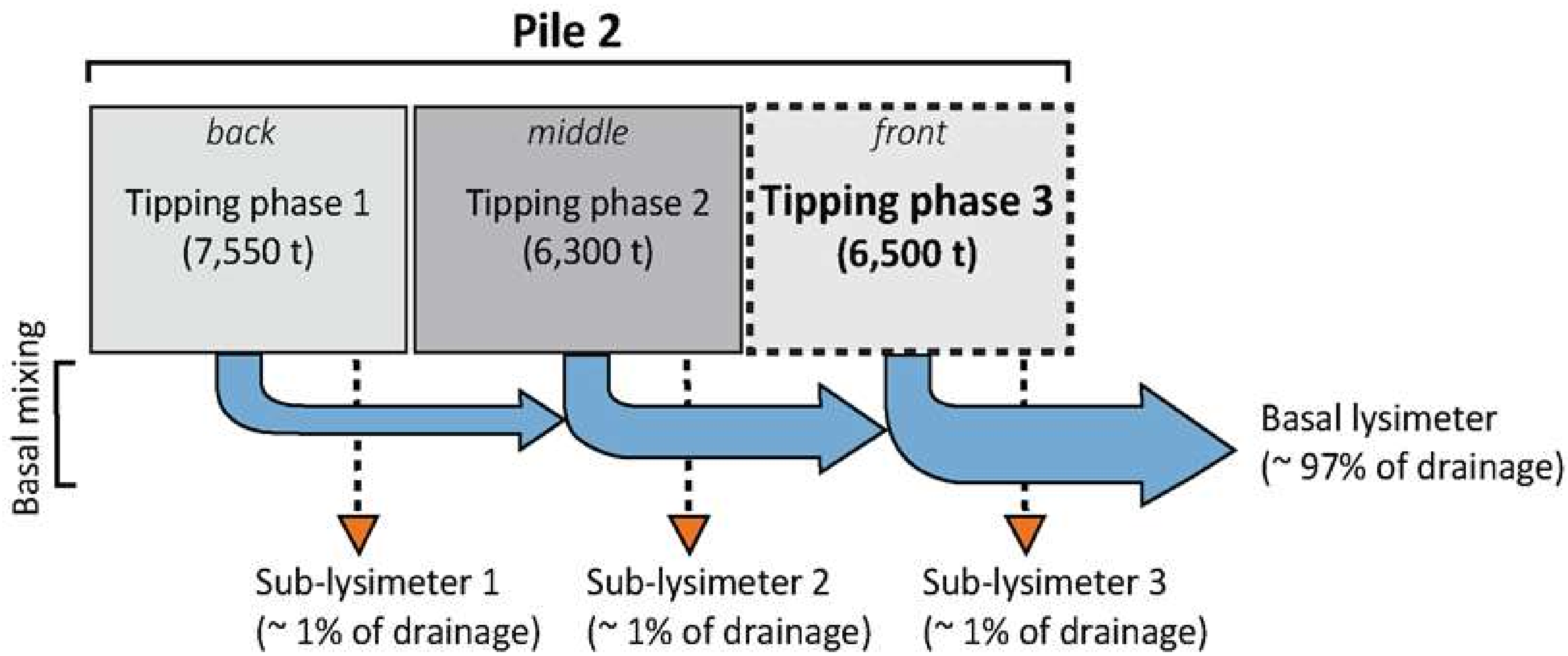
Timing of drainage acidification

Drainage acidification before depletion of neutralizing capacity!



- ineffective neutralization by carbonate?
- slow silicate dissolution kinetics?
- occlusion of buffering minerals?

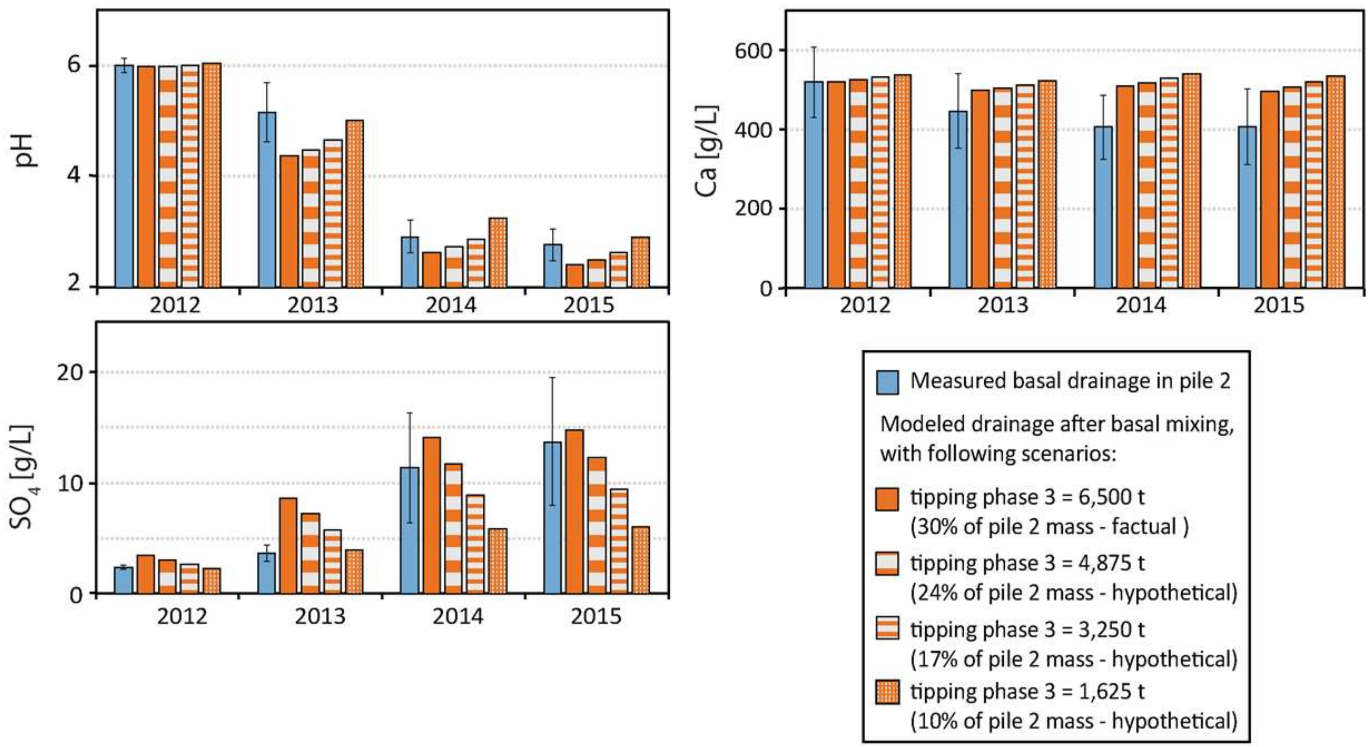
Internal (basal) drainage mixing



Pile 2	Tipping phase 1	Tipping phase 2	Tipping phase 3
S (%)	2.06	0.79	**1.95**
Carbonate-CO_3 (%)	0.4	0.2	**0.1**
AP (t $CaCO_3$ / 1000 t)	70	20	**59**
NP (t $CaCO_3$ / 1000 t)	20	8	**7**

Dominance of acid-generating rock

- Acidic leachate from most reactive tipping phase dominated overall basal drainage quality
- Carbonate-alkalinity concentrations in infiltrating porewater are strongly solubility-limited, whereas acidity is not
- Weight fractions <10% can dominate drainage signature!



Vriens et al., 2019, Chemosphere

Practical implications

1. Seasonal and long-term variations in drainage quality only partially related to waste rock mineralogy, particle size or hydrology

2. Drainage quality also impacted by (temporary) element retention due to <u>adsorption</u>, <u>secondary mineral formation</u>, <u>basal mixing</u>, etc.

3. Mitigation of peak concentrations and seasonal variations in drainage quality requires quantitative understanding of:
    - → abovementioned processes
    - → *in-situ* pore conditions in waste-rock piles
    - → spatial distribution of reactive waste rock

Thank you!

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