A Ten-Year Waste-Rock Study:

Lessons Learned from Multiple Scales and Impact on Prediction

ANTAMINA WASTE ROCK STUDY

Project goals

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

- Operational criteria
- Closure planning

Site description - Antamina

- Located at 4300-4800 MASL
- Alpine climate with bimodal precipitation
- Cu-Zn skarn deposit
- Mills 130 kt/day
- Waste rock produces drainage with circum-neutral pH
- Metals of concern include As, Cu, Zn and Mo

ANTAMINA WASTE ROCK STUDY

Polymetalic skarn

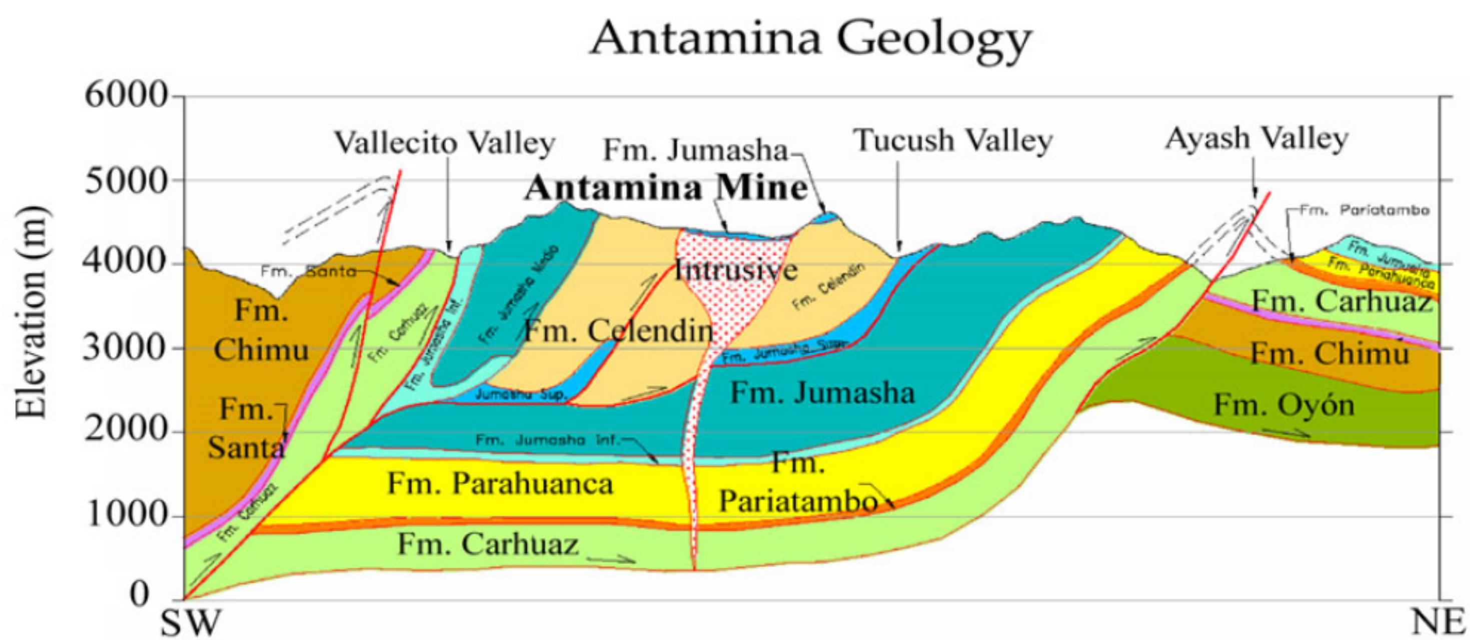
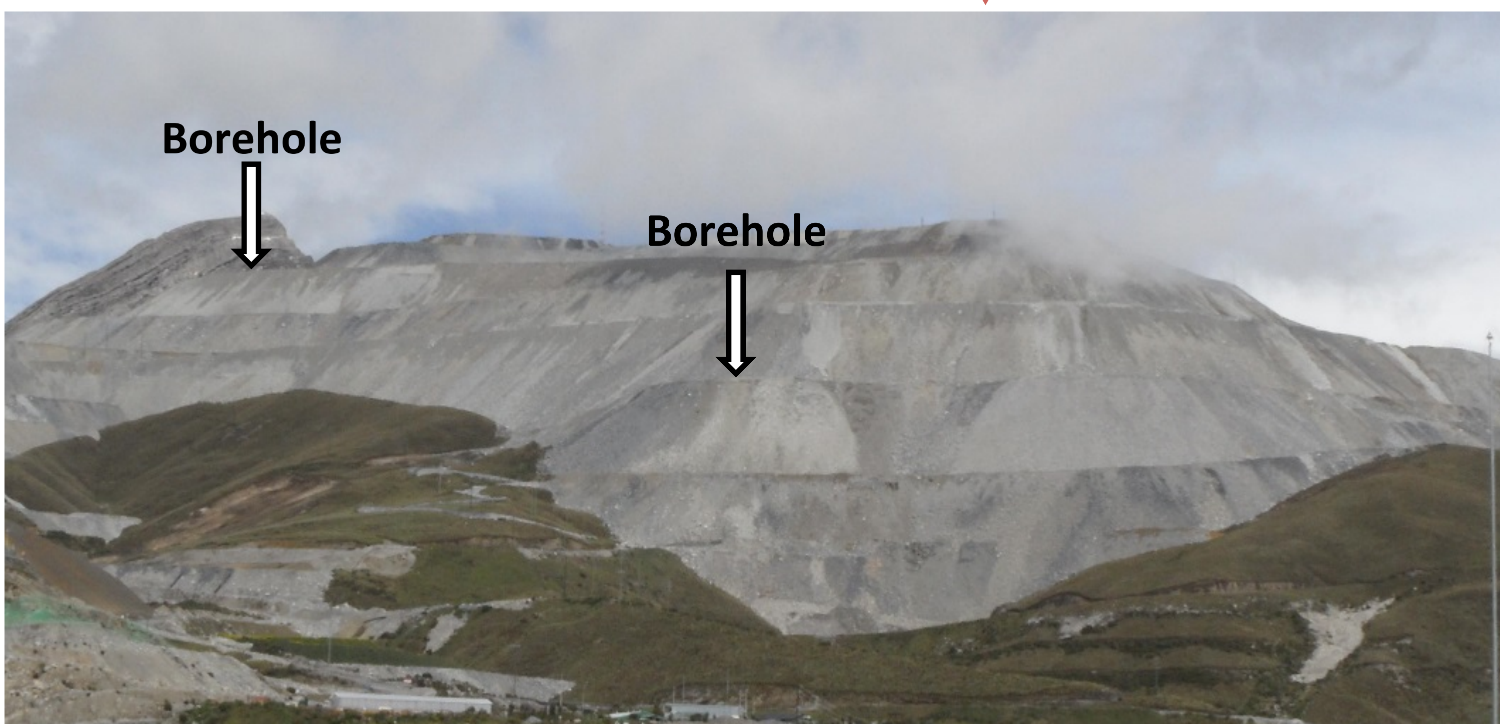


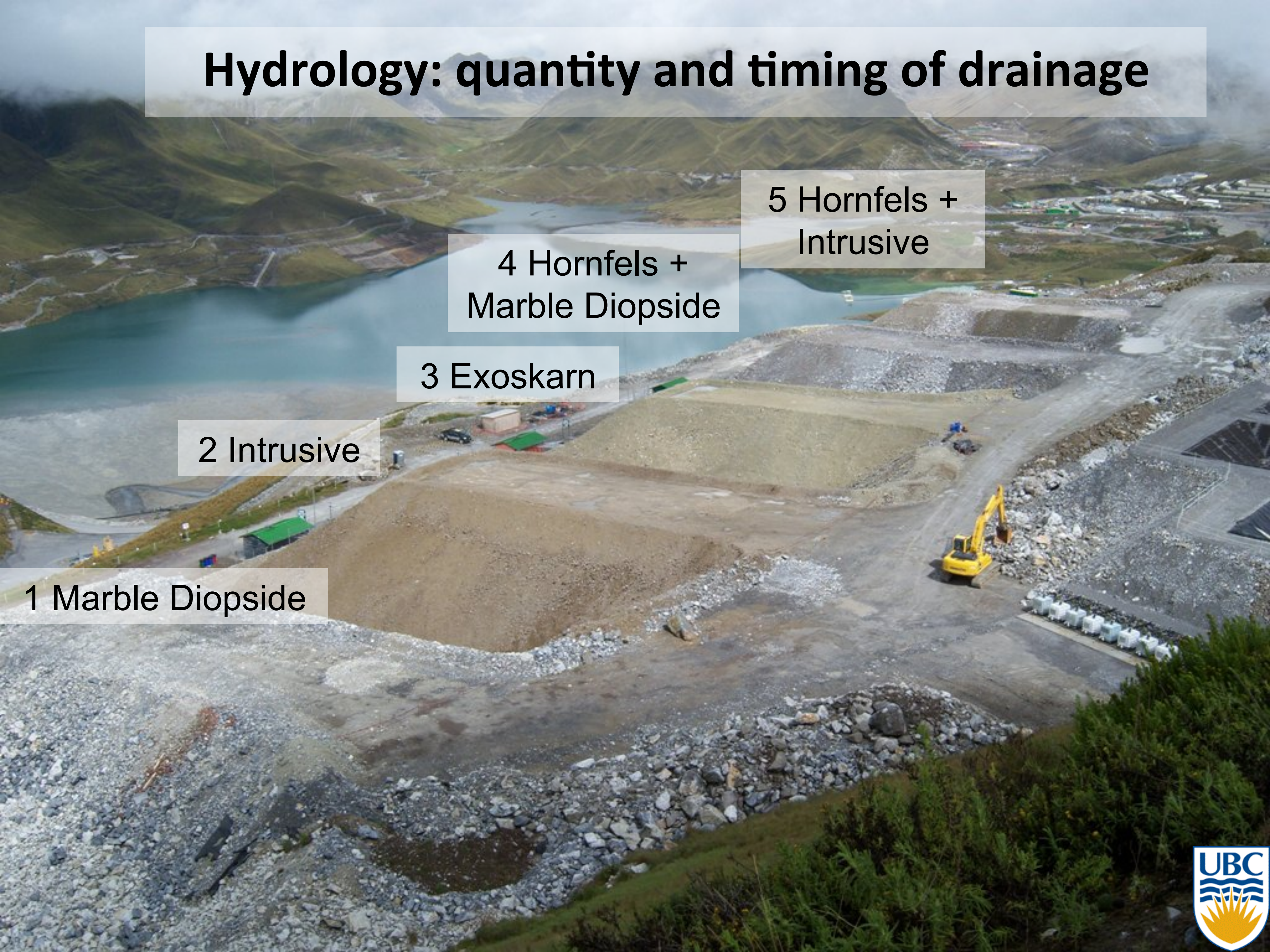
Figure 1.2 – Cross section of the geology at Antamina (modified from Lipten, 2003)

Multi-scale investigation



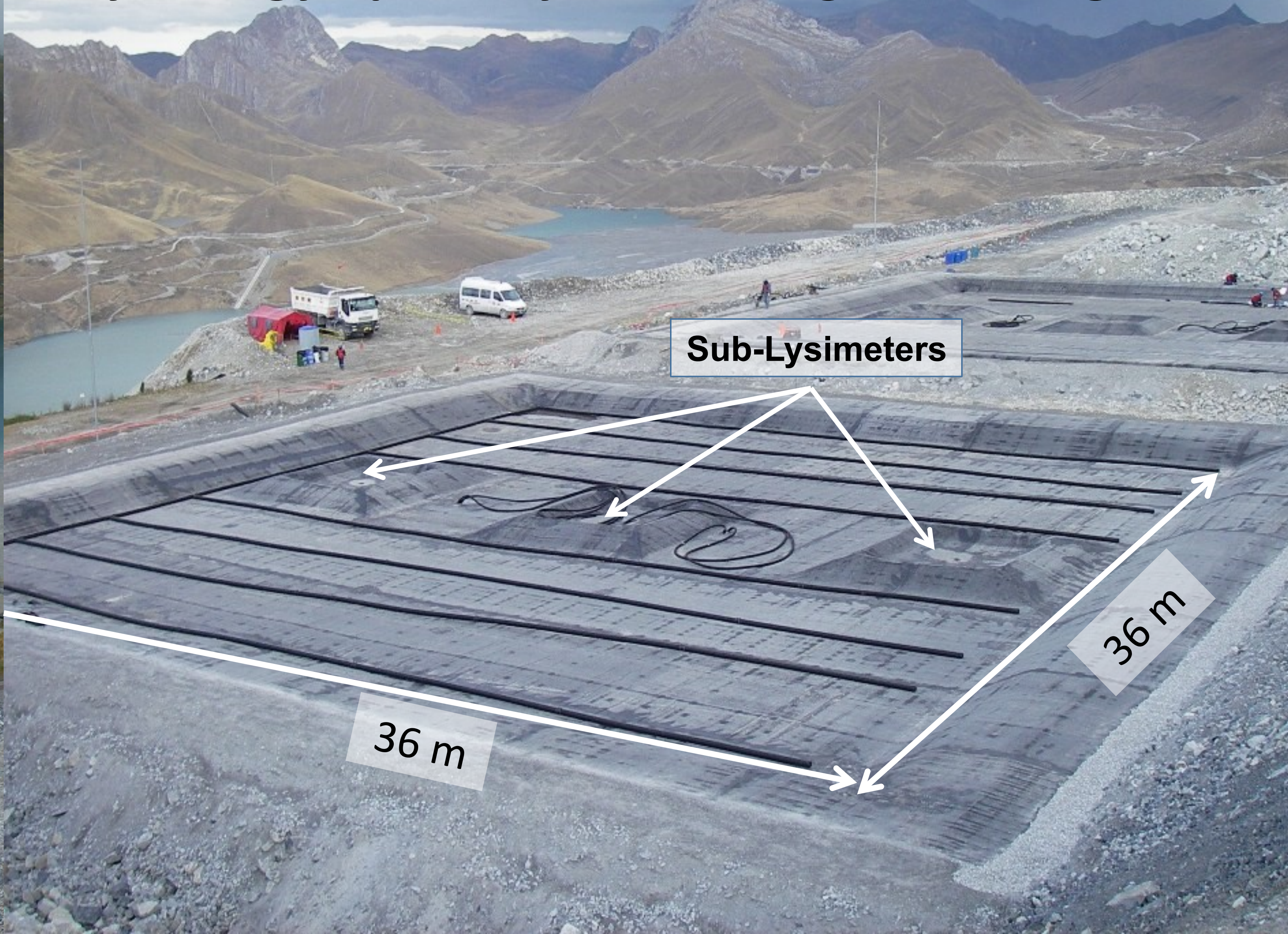

PELIGRO

Hydrology: quantity and timing of drainage



ANTAMINA WASTE ROCK STUDY

Hydrology: quantity and timing of drainage



ANTAMINA

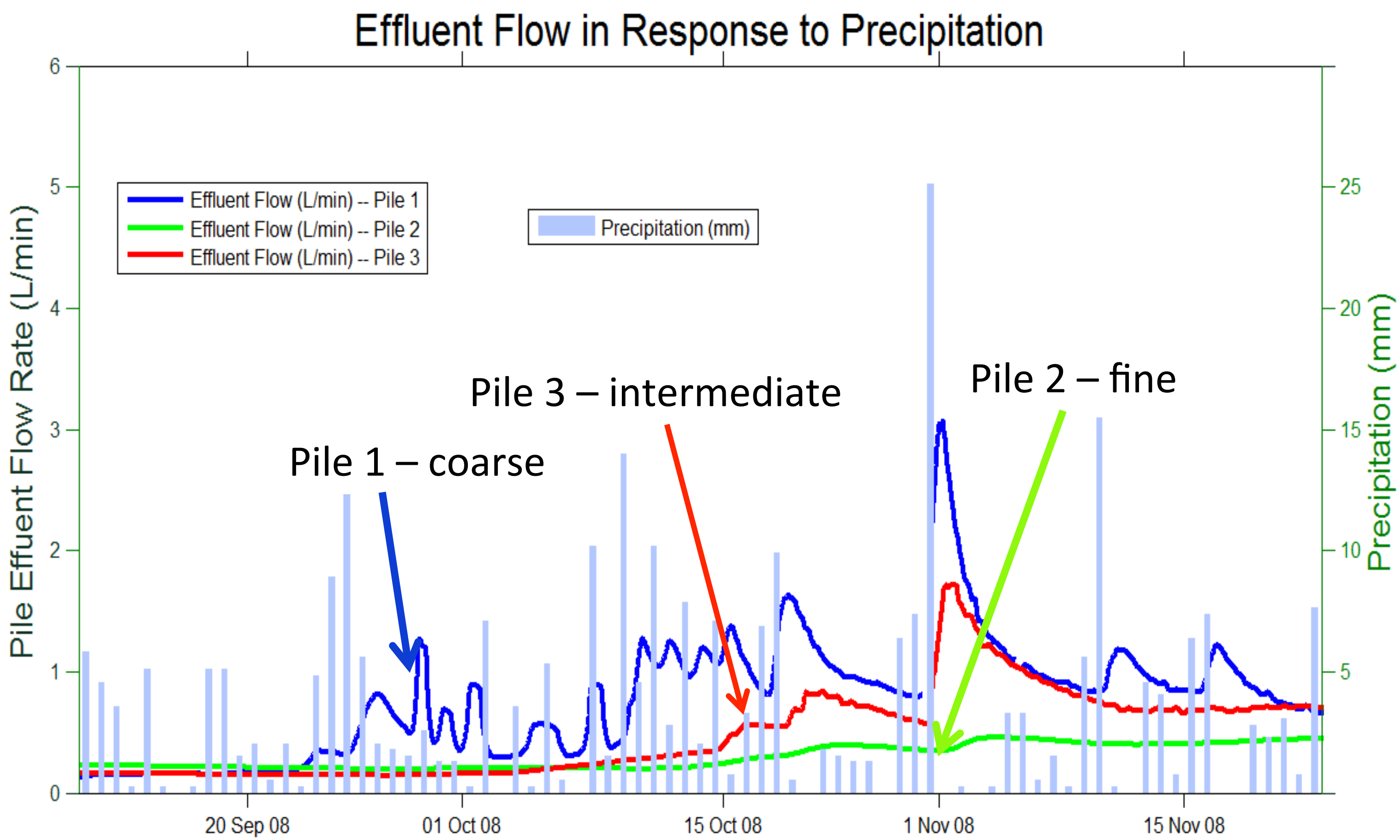
NSERC CRSNG

Teck

UBC

Discharge hydrographs from piles

- Distinct fast & slow flow regimes observed
- Unique response for each pile



ANTAMINA WASTE ROCK STUDY

ANTAMINA

NSERC CRSNG

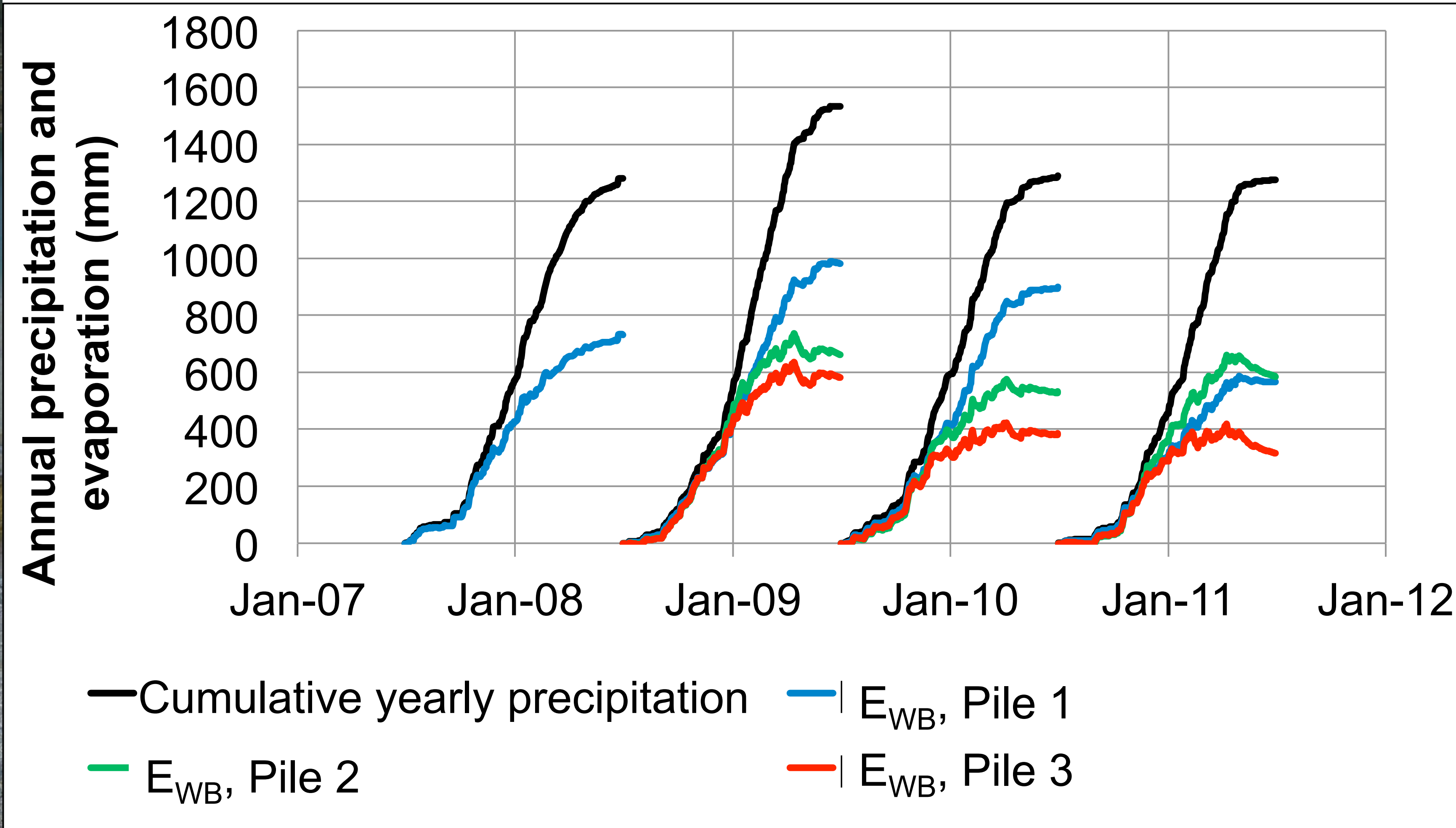
Teck

UBC

Evaporation

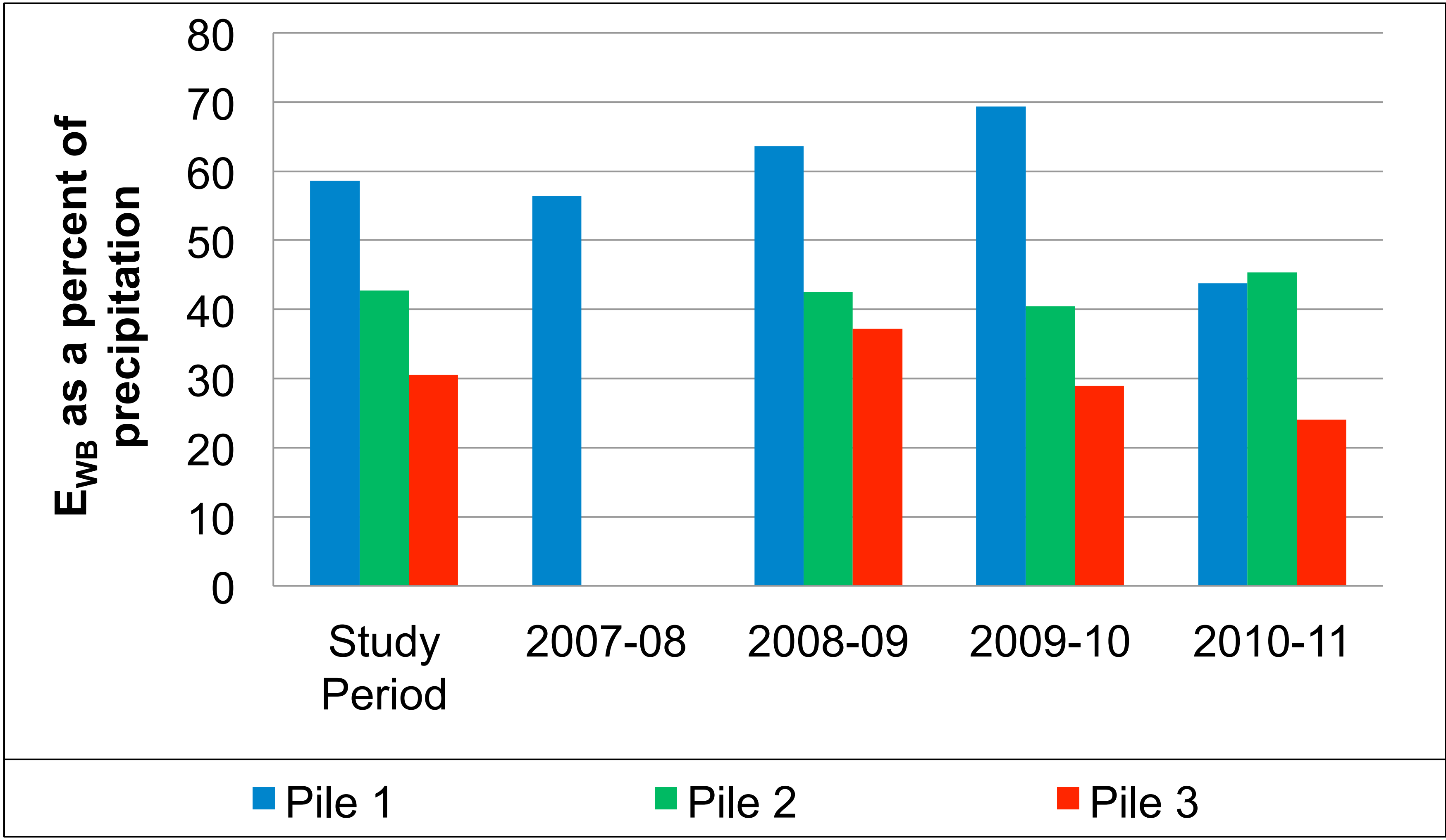
Grain size → strong control

Inter-annual variability



Evaporation (% of precipitation)

➔ Large differences among piles



ANTAMINA WASTE ROCK STUDY

Scale-up of evaporation

Different geometries

Scale-up of evaporation

Test-pile scale

Different geometries

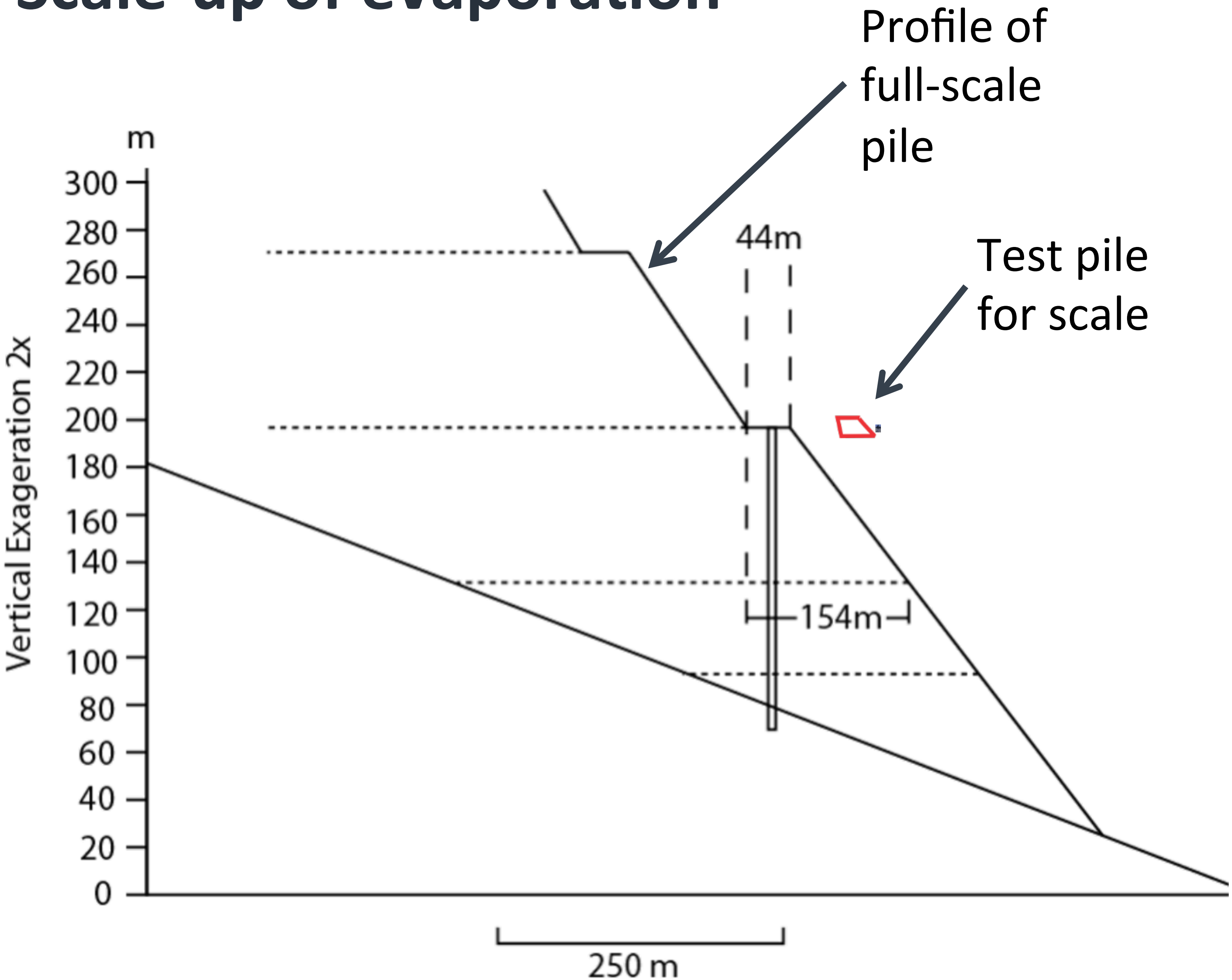
Full scale

ANTAMINA WASTE ROCK STUDY

Scale-up of evaporation

Different geometries

Scale-up of evaporation



ANTAMINA WASTE ROCK STUDY

Lessons learned

- Evaporation from uncovered waste rock greatest uncertainty in water balance
- Evaporation difficult to predict from grain-size distribution and local climate
- Local evaporation strongly depends upon material type and surface condition

➔ Easy to measure through lysimeter experiments at test-pile scale

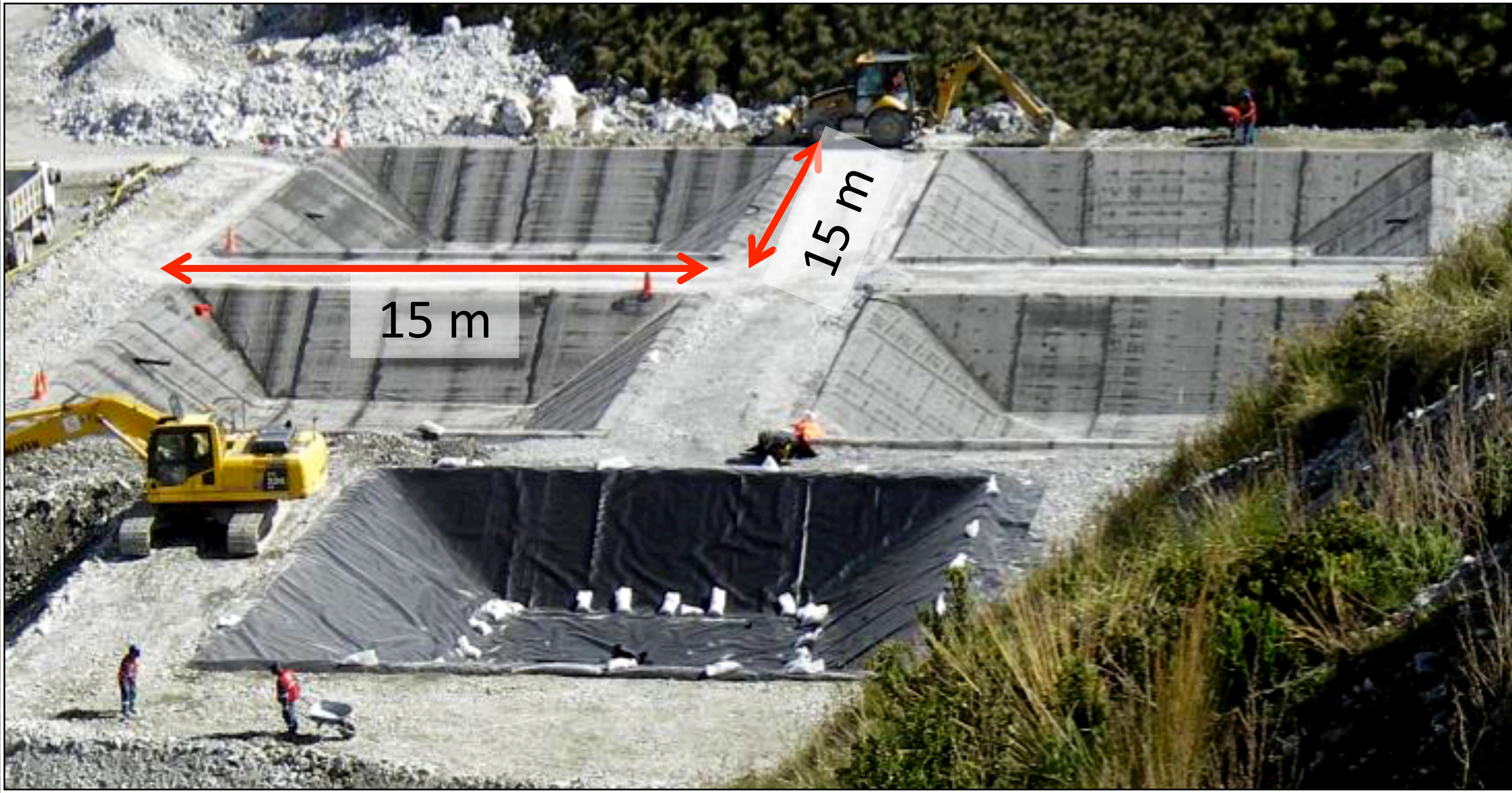
$$P = ET + D + RO$$

ANTAMINA WASTE ROCK STUDY

Soil-cover system

- Objective: Determine the best closure alternative for the waste-rock
- How?
  - Evaluate the performance of four cover systems and one control system, by measuring infiltration and runoff (4 years of monitoring).
  - Measure in-situ soil properties after construction.
  - Evaluate alternatives to improve cover performance using SoilCover models.

Cover experiment lysimeters



ANTAMINA WASTE ROCK STUDY

ANTAMINA

NSERC CRSNG

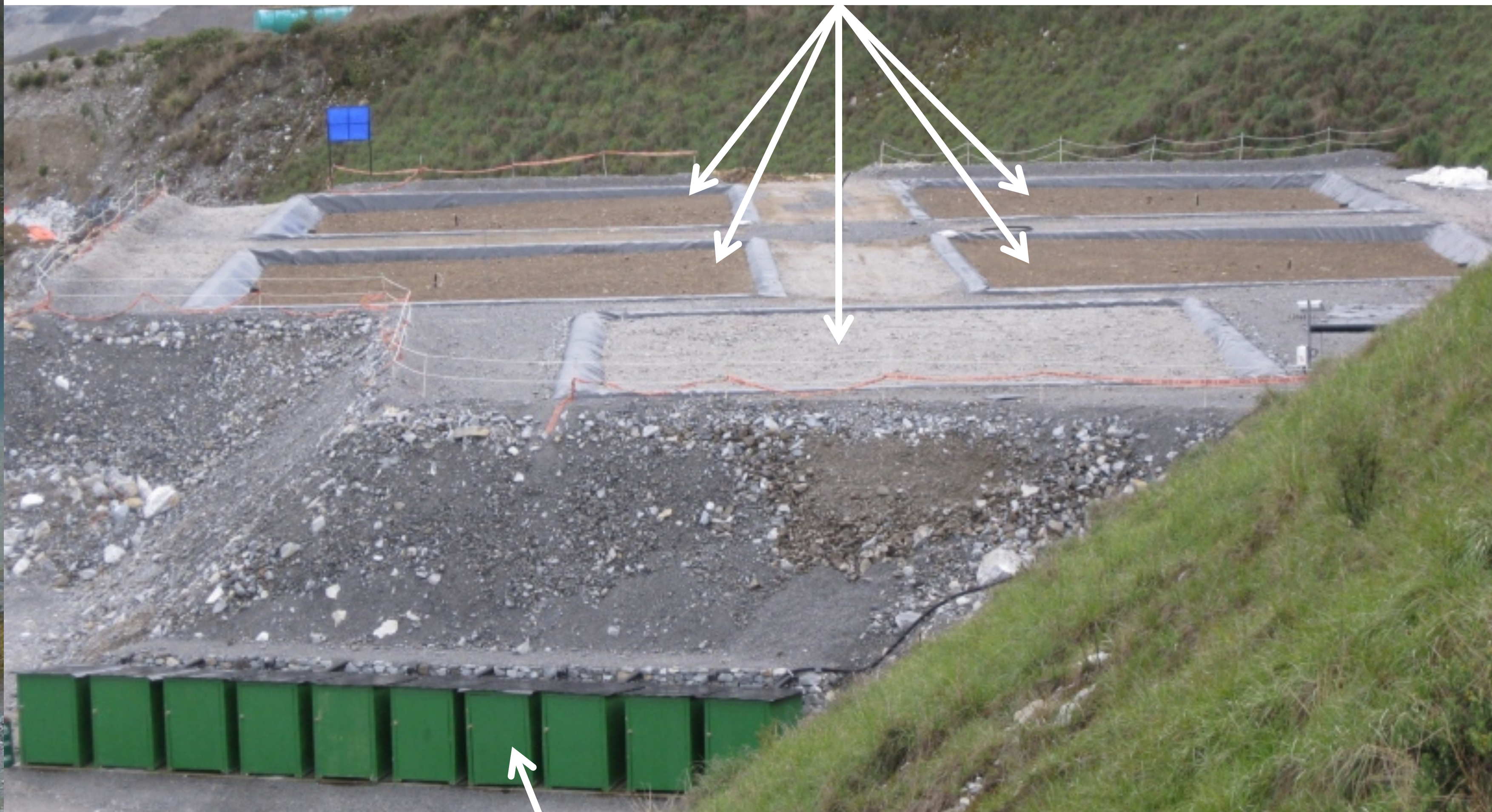
Teck

UBC

ANTAMINA WASTE ROCK STUDY

Cover experiments

5 test covers

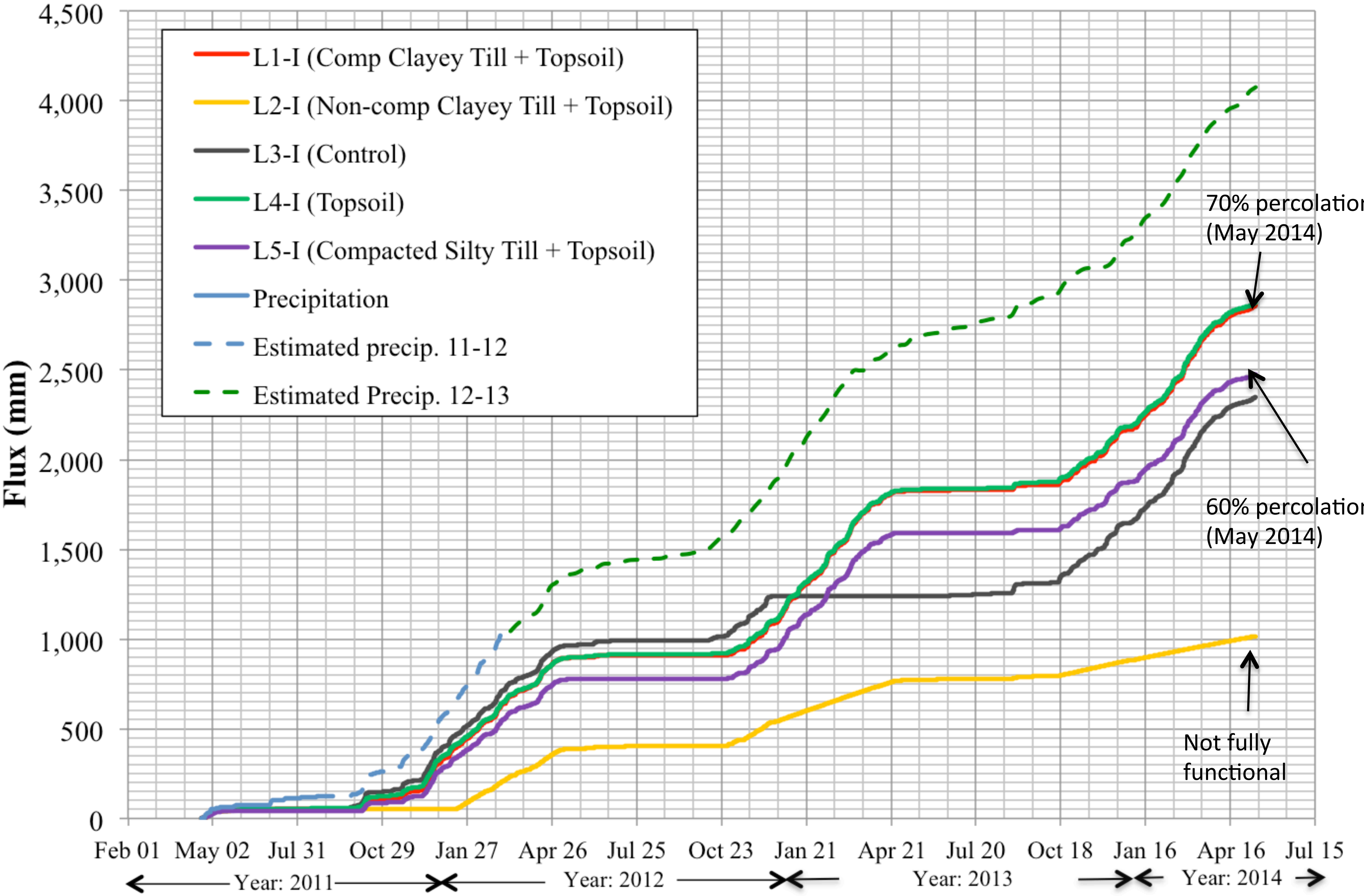


Instrumentation huts

Cover designs

Lysimeter	Cover Layers			
	Layer 1		Layer 2	
	Material	Thickness	Material	Thickness
#1	Compacted Glacial Till	600 mm	Topsoil	300 mm
#2	Non-comp. Glacial Till	600 mm	Topsoil	300 mm
#3	None (Control)	-	-	-
#4	-	-	Topsoil	300 mm
#5	Compacted Colluvium	600 mm	Topsoil	300 mm

Cover System Performance



ANTAMINA WASTE ROCK STUDY

Infiltration

- Covered waste rock: 41% - 70% of precipitation

- Uncovered test piles: 60% - 75% of precipitation

Covers have not reduced infiltration

Lessons learned

- Cover performance depends on weather AND cover characteristics.
- Net infiltration>50% of total precipitation.
- No runoff. Why? Rainfall intensity not high enough + higher K_{SAT} of low permeability barrier material.
- Compaction of barrier layer: not an advantage.
- Laboratory soil properties could not be replicated in the field.
- Performance might be improved, but at risk of erosion problems.
- Field study: necessary to account for local/specific conditions and to assess predictions.

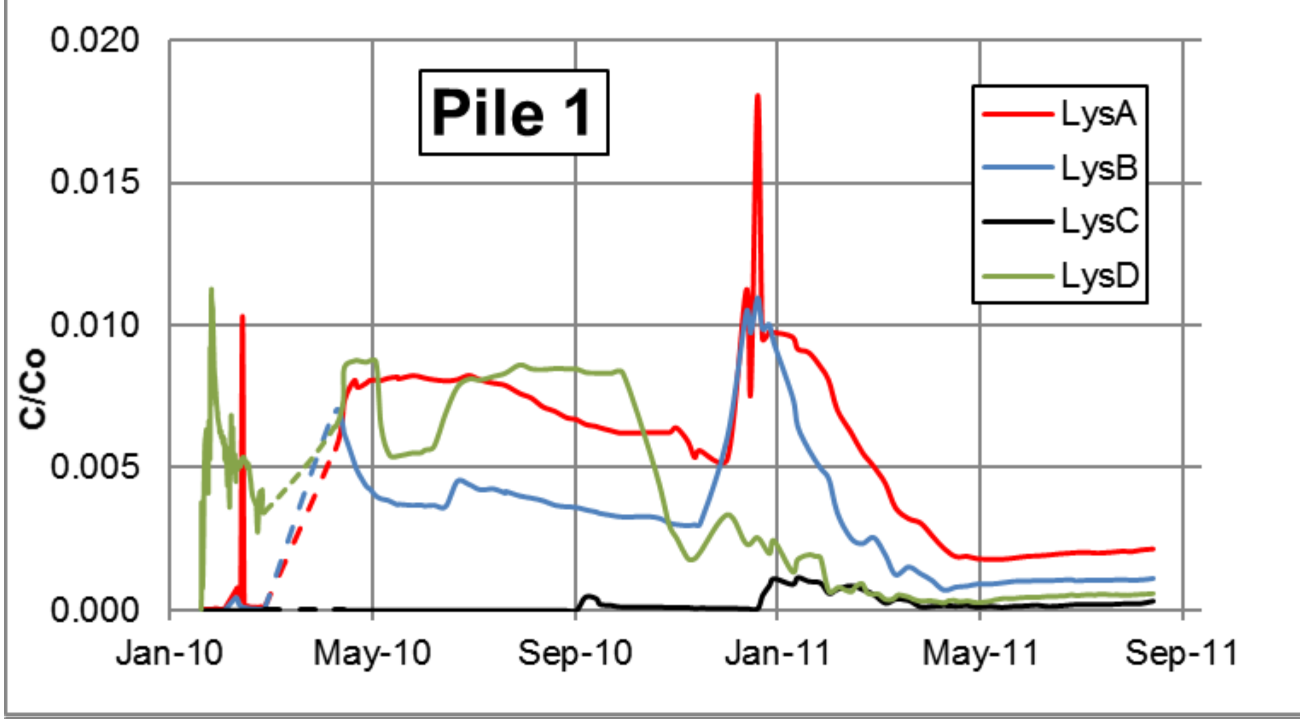
ANTAMINA WASTE ROCK STUDY

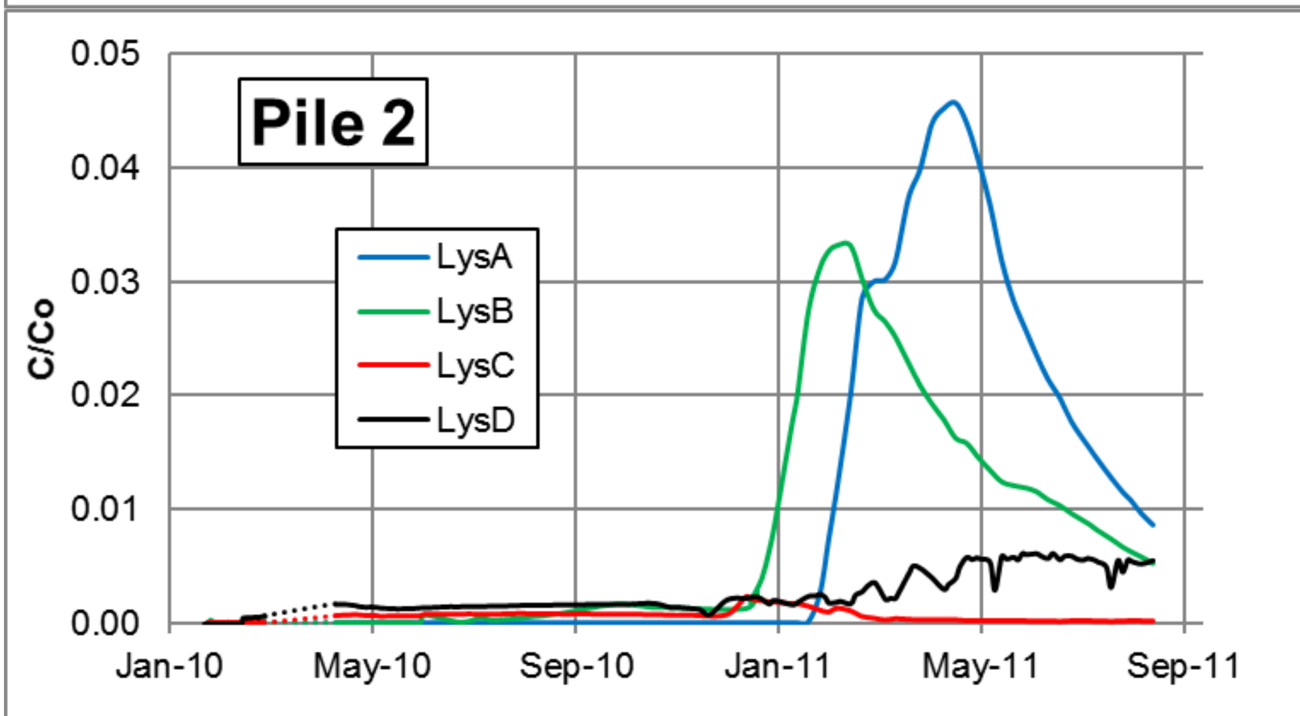
Transport in waste rock

ANTAMINA
NSERC CRSNG
Teck
UBC

ANTAMINA WASTE ROCK STUDY

Tracer break through





ANTAMINA

NSERC CRSNG

Teck

UBC

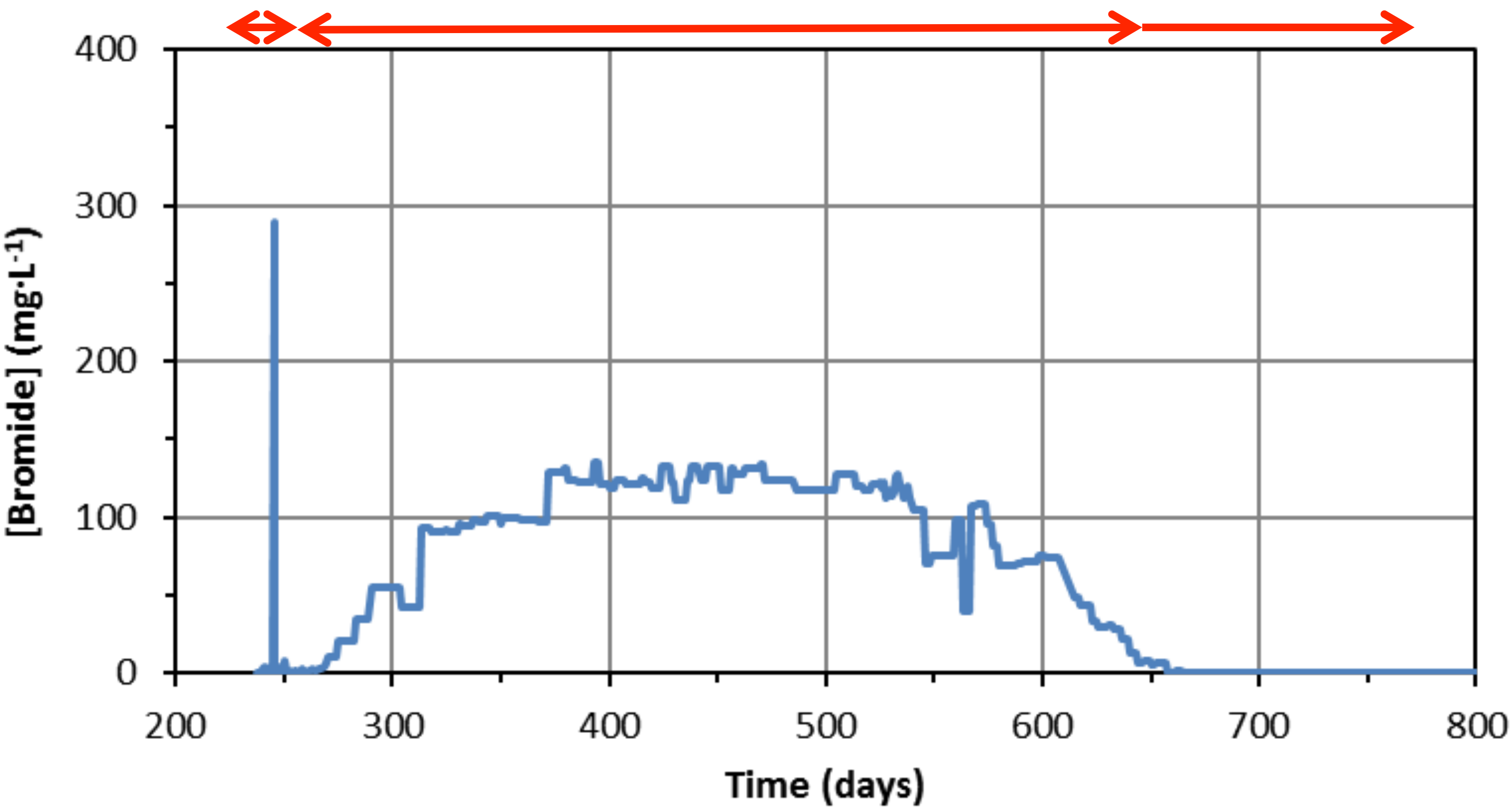
ANTAMINA WASTE ROCK STUDY

Tracer breakthrough

very fast
>1 % of mass

matrix
~80 % of mass

slow
~20 % of mass



$$K \sim 11\ m/400\ d = 3\times10^{-7}\ m/s$$

Multi-permeability system

Very fast

- >1% mass through pile in hours to few days

Matrix flow

- ~80 % mass “conventional” unsaturated flow

Slow flow paths, “immobile” zones

- ~20 % mass

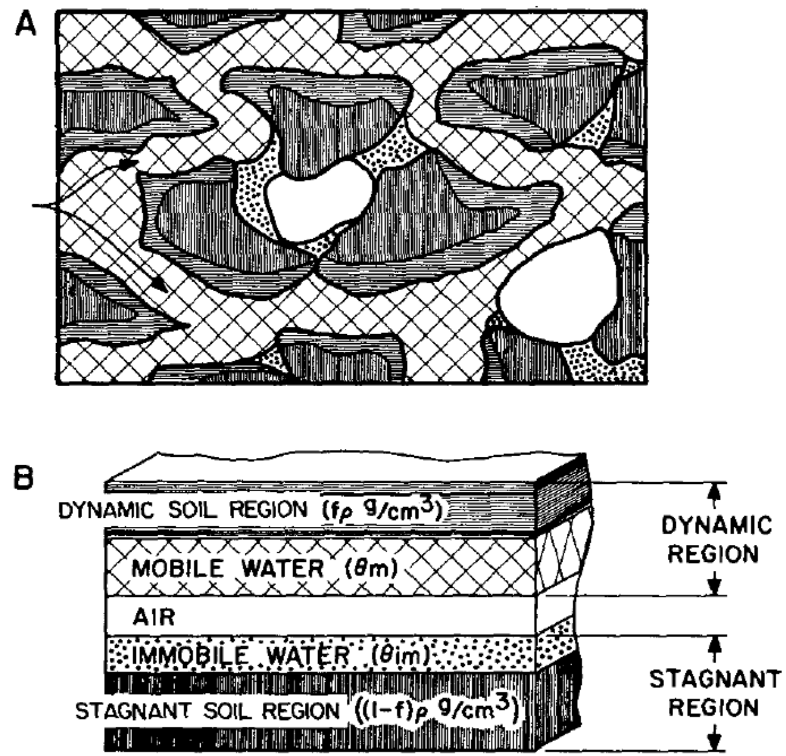


Fig. 1—Schematic diagram of unsaturated aggregated porous medium. (A) Actual model. (B) Simplified model. The shading patterns in A and B represent the same regions.

Van Genuchten and Wierenga

ANTAMINA WASTE ROCK STUDY

ANTAMINA NSERC CRSNG Teck UBC

Lessons learned

- Heterogeneous waste-rock best conceptualized as a multi-permeability system
- Slow/immobile zones
- Implications for geochemistry: ongoing

ANTAMINA WASTE ROCK STUDY

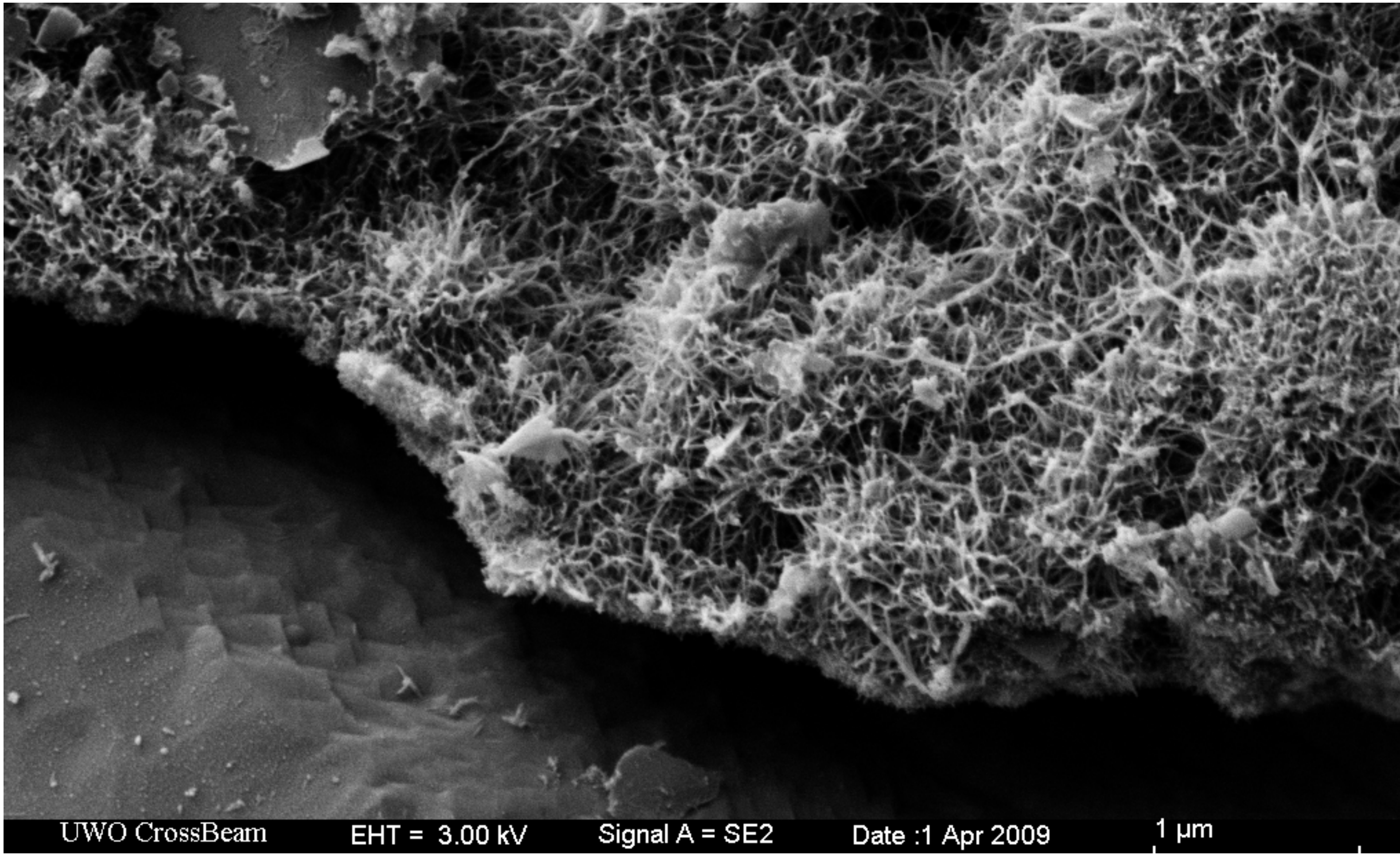
Release and attenuation mechanisms

Methods

- Microscopies
- Quantitative mineralogy: XRD, EDS
- Mineral Liberation Analysis
- Bulk acid-base accounting
- Sequential extractions on weathered rocks
- Humidity cells
- Field barrels
- Depth profiles from boreholes in full-scale piles

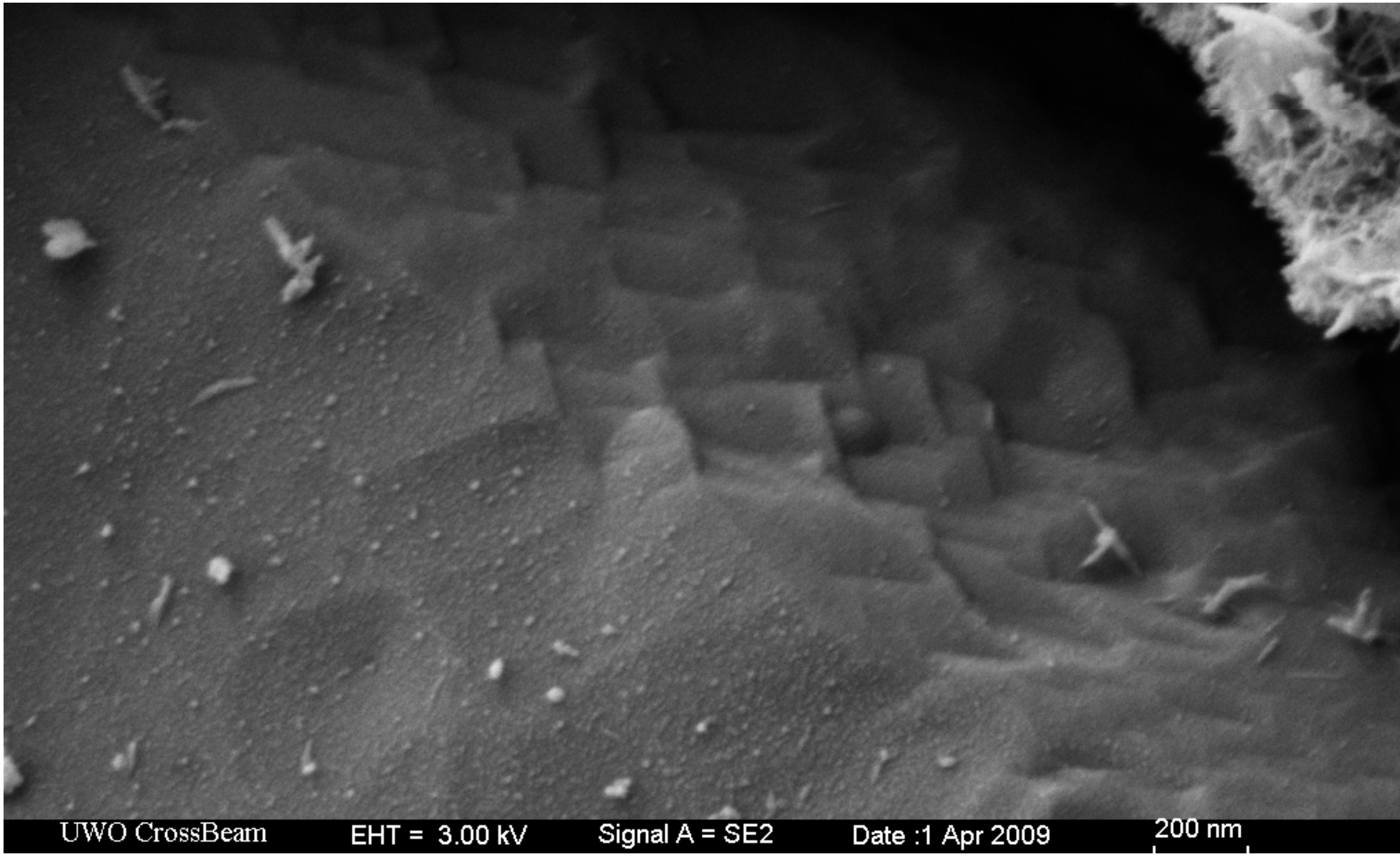
ANTAMINA WASTE ROCK STUDY

Microenvironments



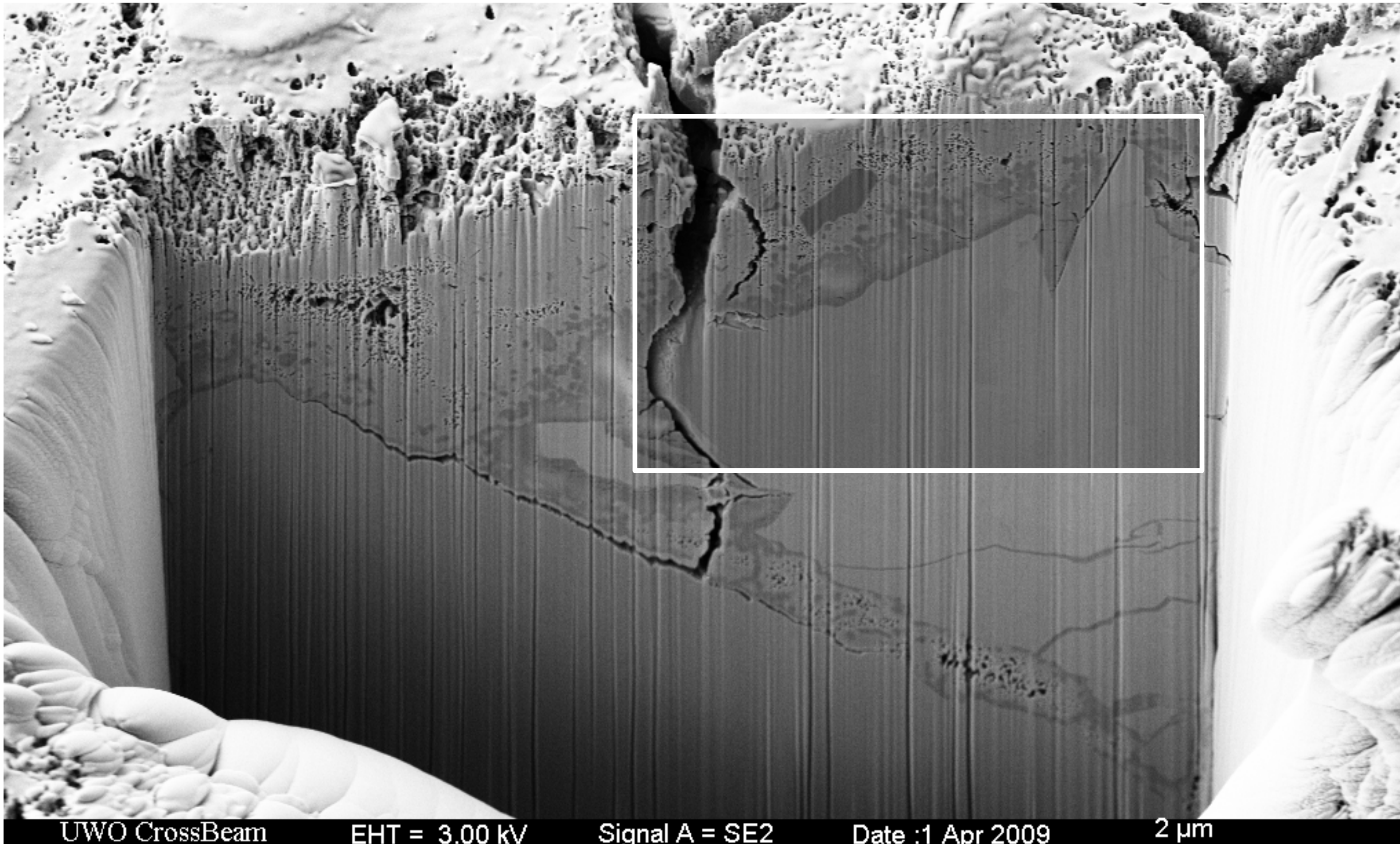
Pitting in pyrrhotite beneath microbially populated schwertmannite

Microenvironments



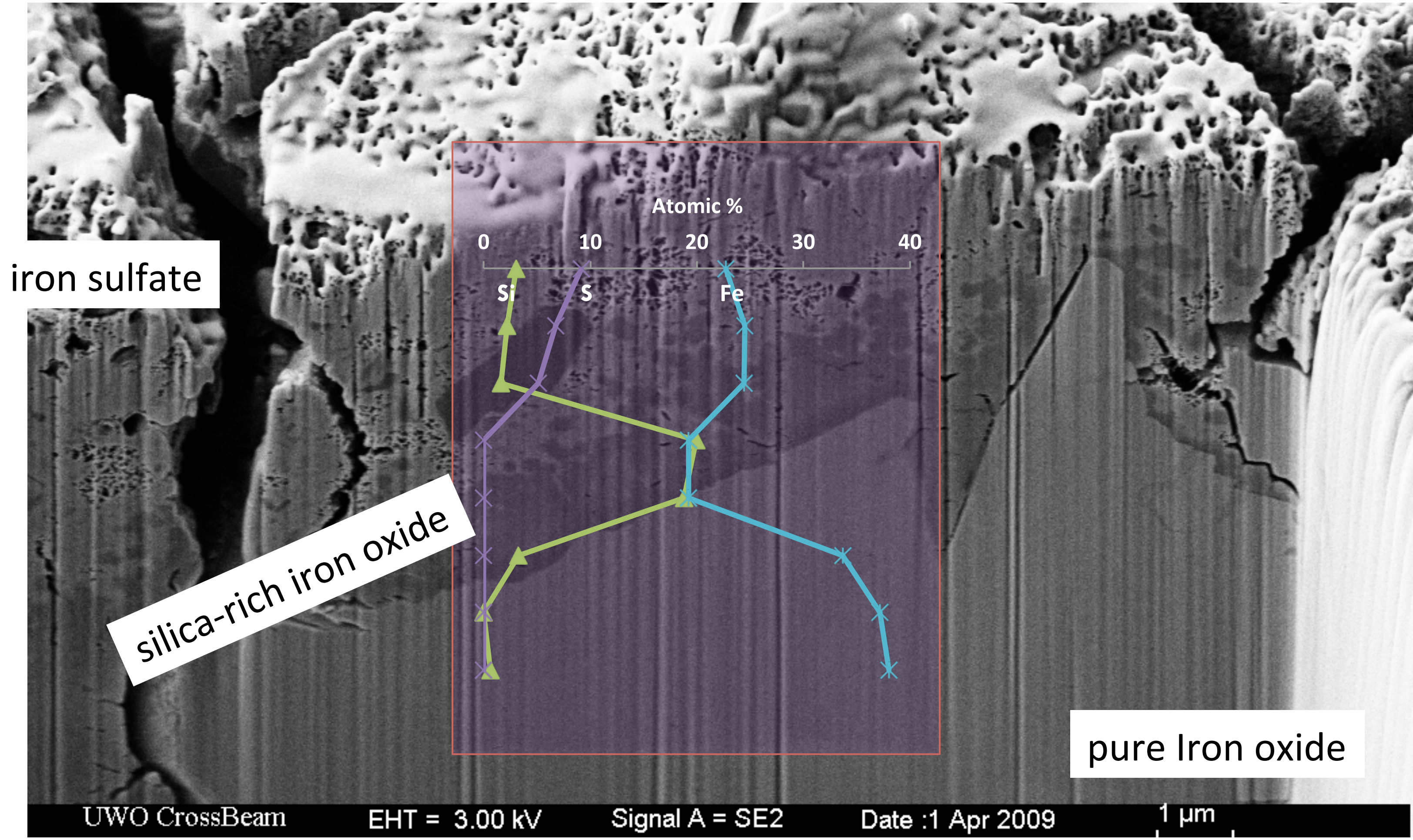
Pyrrhotite beneath microbially inhabited schwertmannite has been more severely weathered then uncovered surfaces

Focused ion beam (FIB)

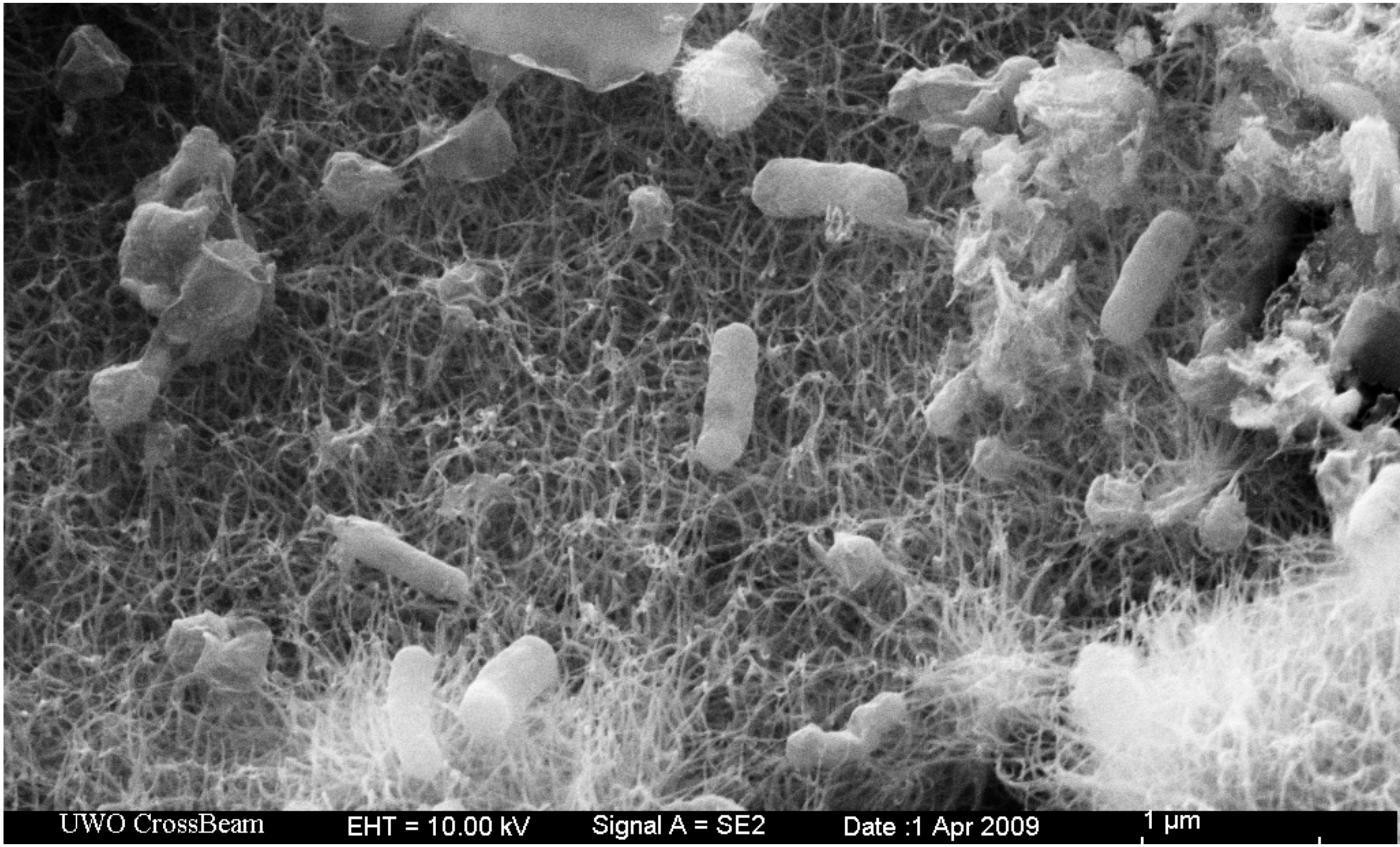


FIB cut through iron oxide coating exposing cross section

Energy Dispersive Spectroscopy (EDS)



Microenvironments

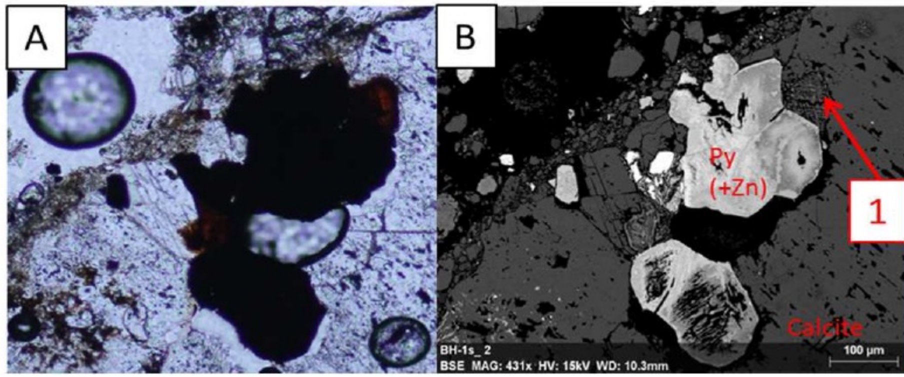


Geochemically isolated conditions provided by the porosity of the schwertmannite bound by the overlying non-porous crust

ANTAMINA WASTE ROCK STUDY

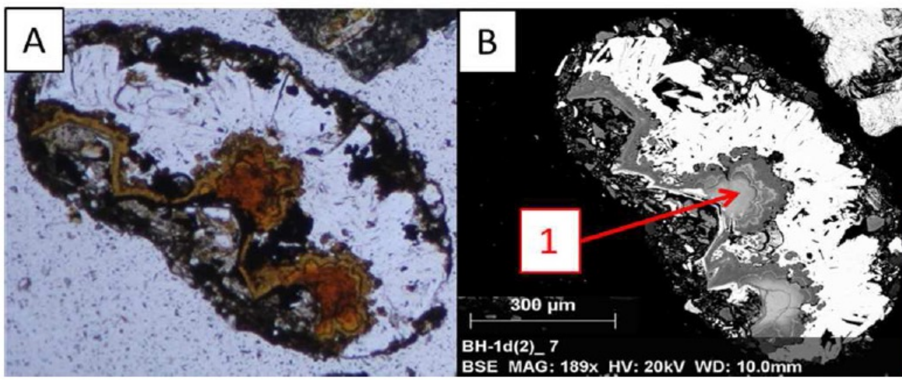
Microscopy

Plane Polarized | SEM | EDS



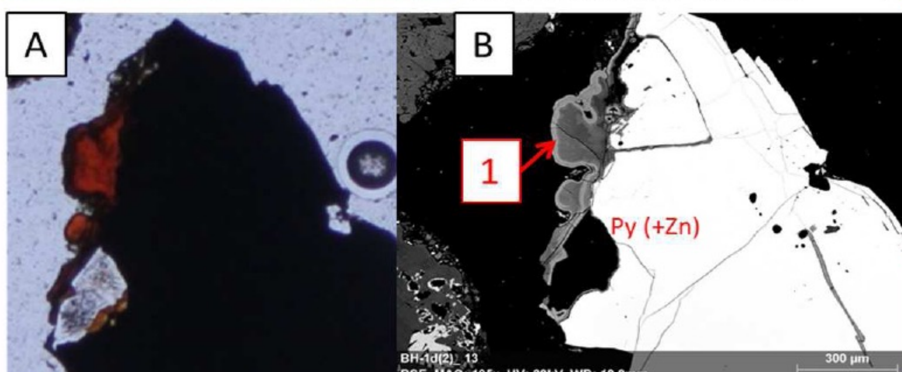
	1
	wt. %
Fe	28
O	21
Zn	1
Pb	4

Iron oxide of weathered sulfides



	1
	wt. %
Fe	41
O	26
Cu	2
Zn	8
Pb	2
Mo	0.01

Iron oxide coating non-sulfide minerals

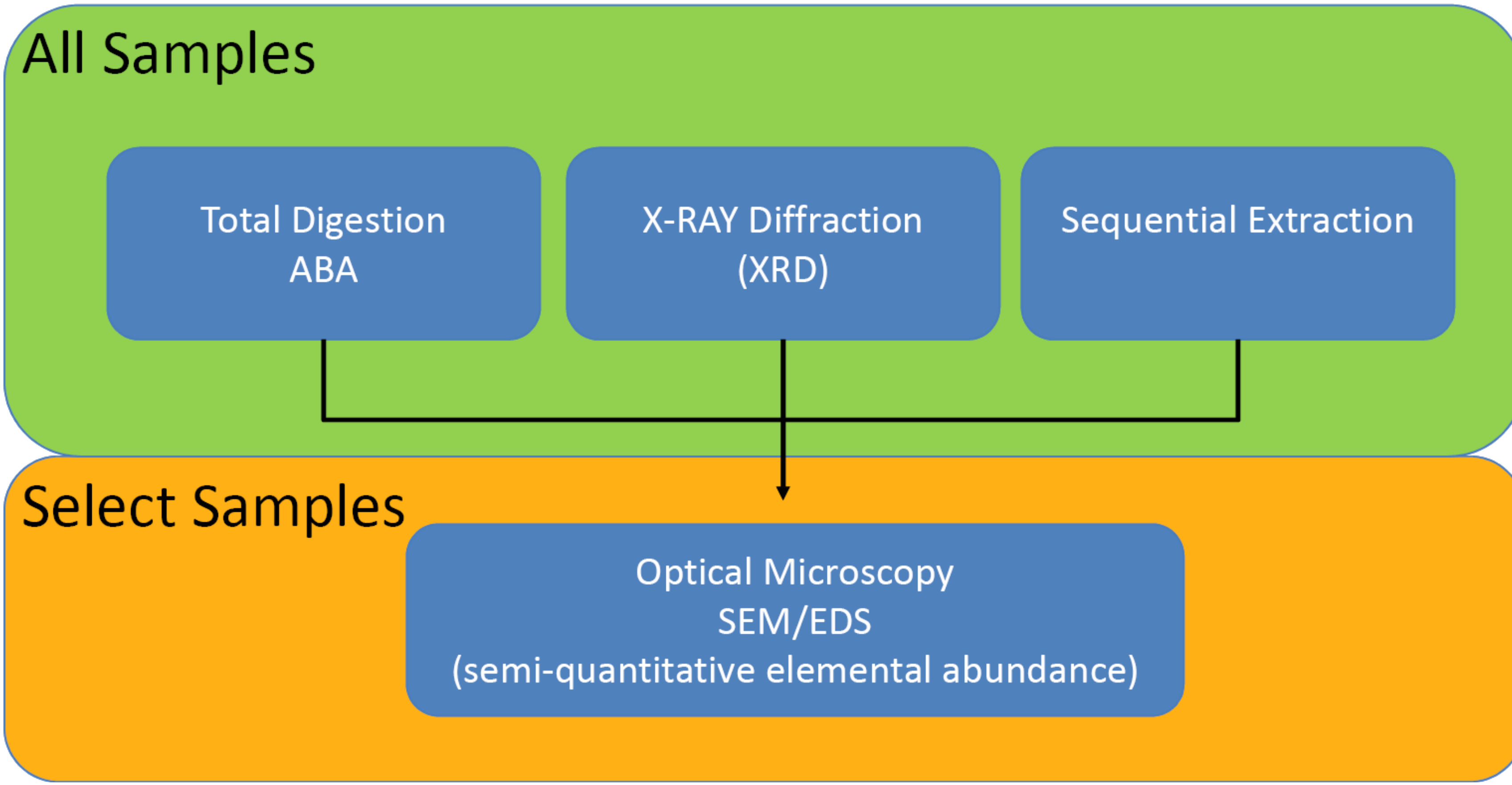


	1
	wt. %
Fe	35
O	30
Cu	2
Zn	1

Iron oxide coating sulfide minerals

ANTAMINA WASTE ROCK STUDY

Sequential extractions



Lessons learned

- Optical, SEM, and quantitative mineralogy to identify processes

➔Establish process-based models

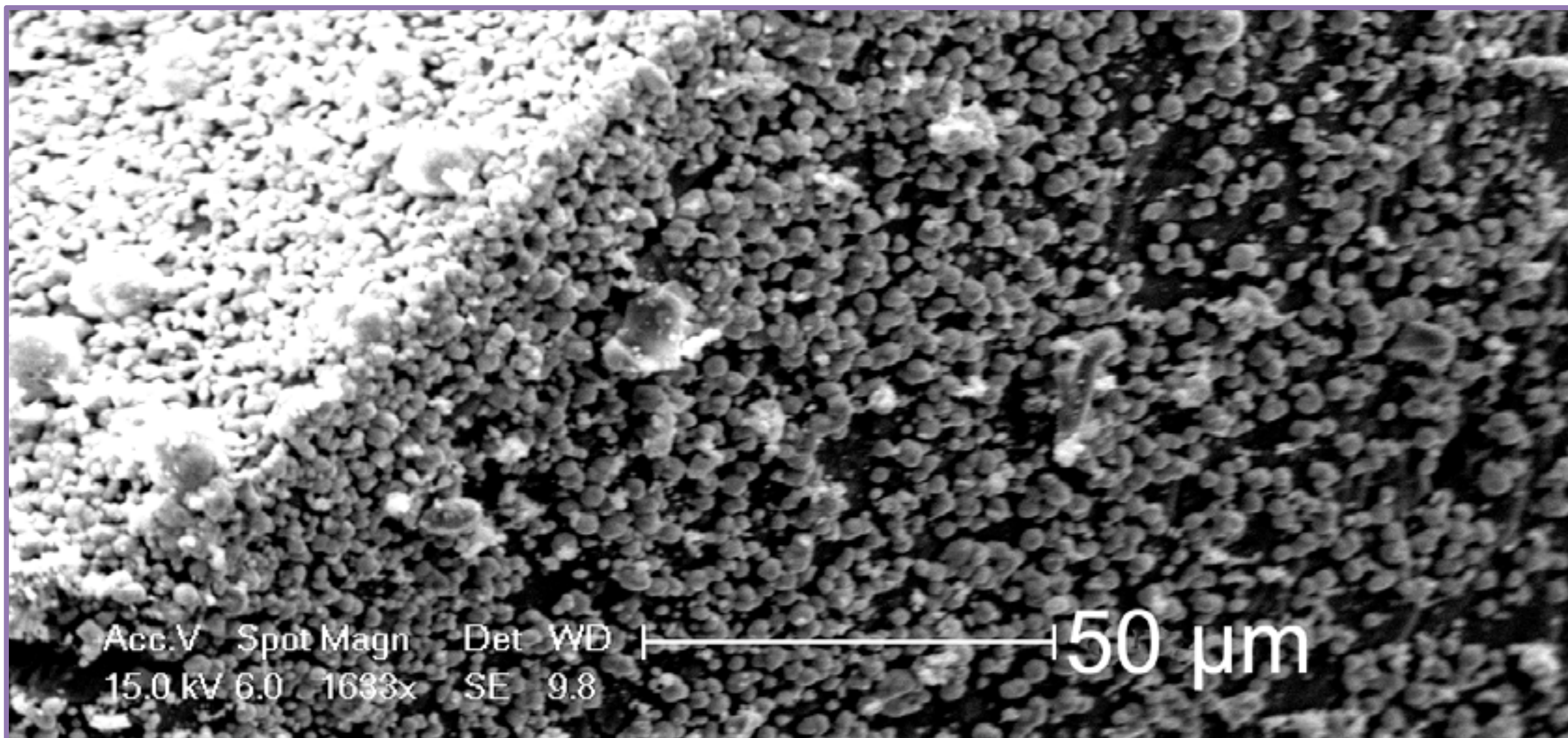
- There is a distinction between bulk (eg ABA) and aggregated behaviors: complementary information

ANTAMINA WASTE ROCK STUDY

Molybdenum attenuation

- Attenuated in two mineral phases:
  - Powellite ($CaMoO_4$)
  - Wulfenite ($PbMoO_4$)

Powellite crystals

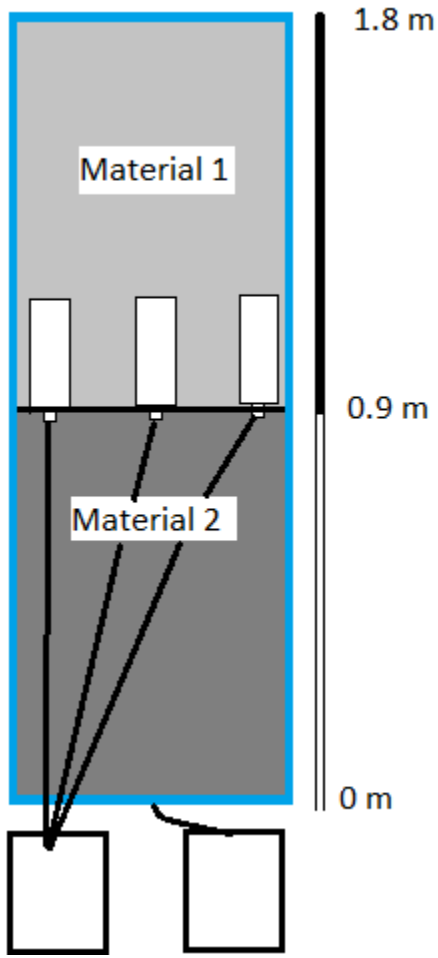


Attenuation and effects of mixing

Can stacking/mixing attenuate metals?

Hypothesis: Pb – rich rock promotes attenuation of Mo by formation of wulfenite ($PbMoO_4$)

Stacked field barrels



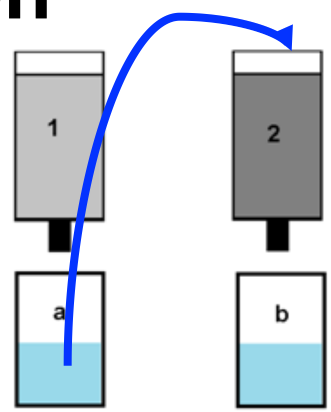
Above: Mo-rich intrusives

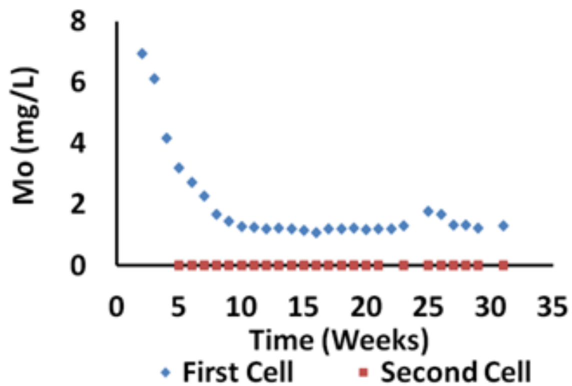
Below: Pb-rich black marble

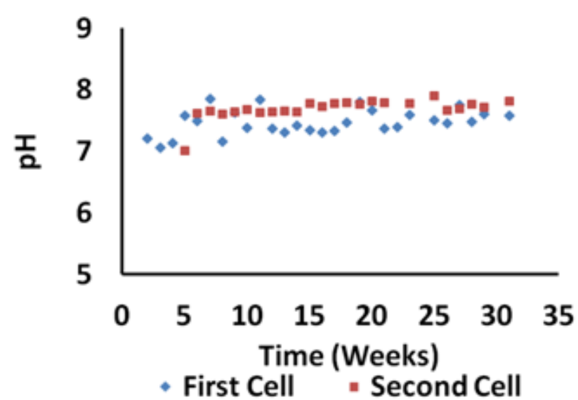
Mo attenuation

Mo releasing
(Intrusive)

Pb-containing
(Black Marble)





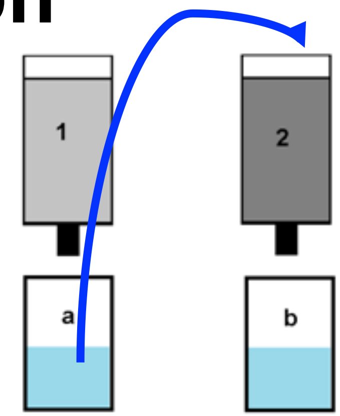


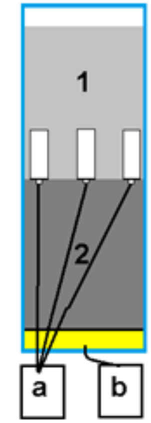
ANTAMINA WASTE ROCK STUDY

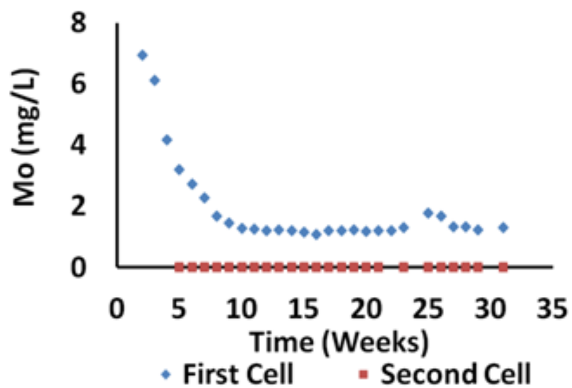
Mo attenuation

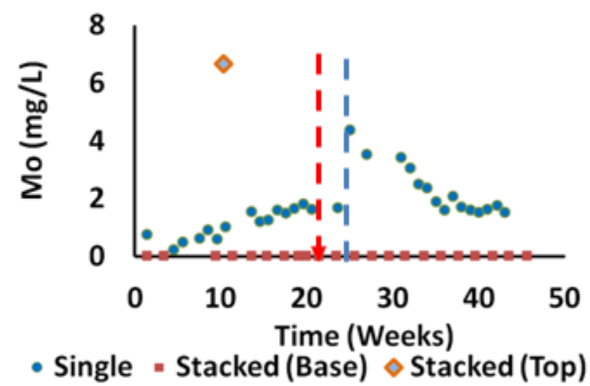
Mo releasing
(Intrusive)

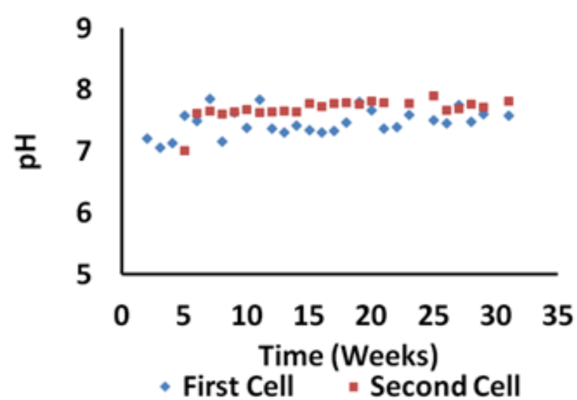
Pb-containing
(Black Marble)

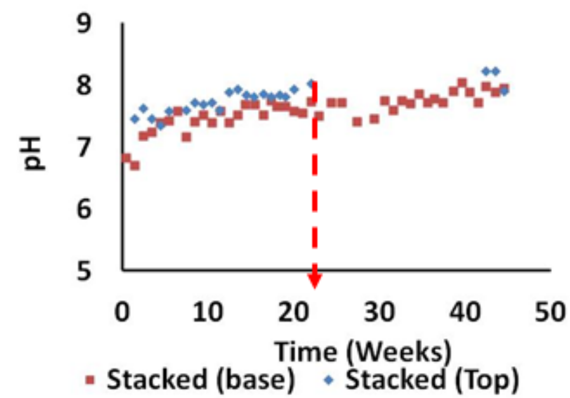












NSERC CRSNG
Teck

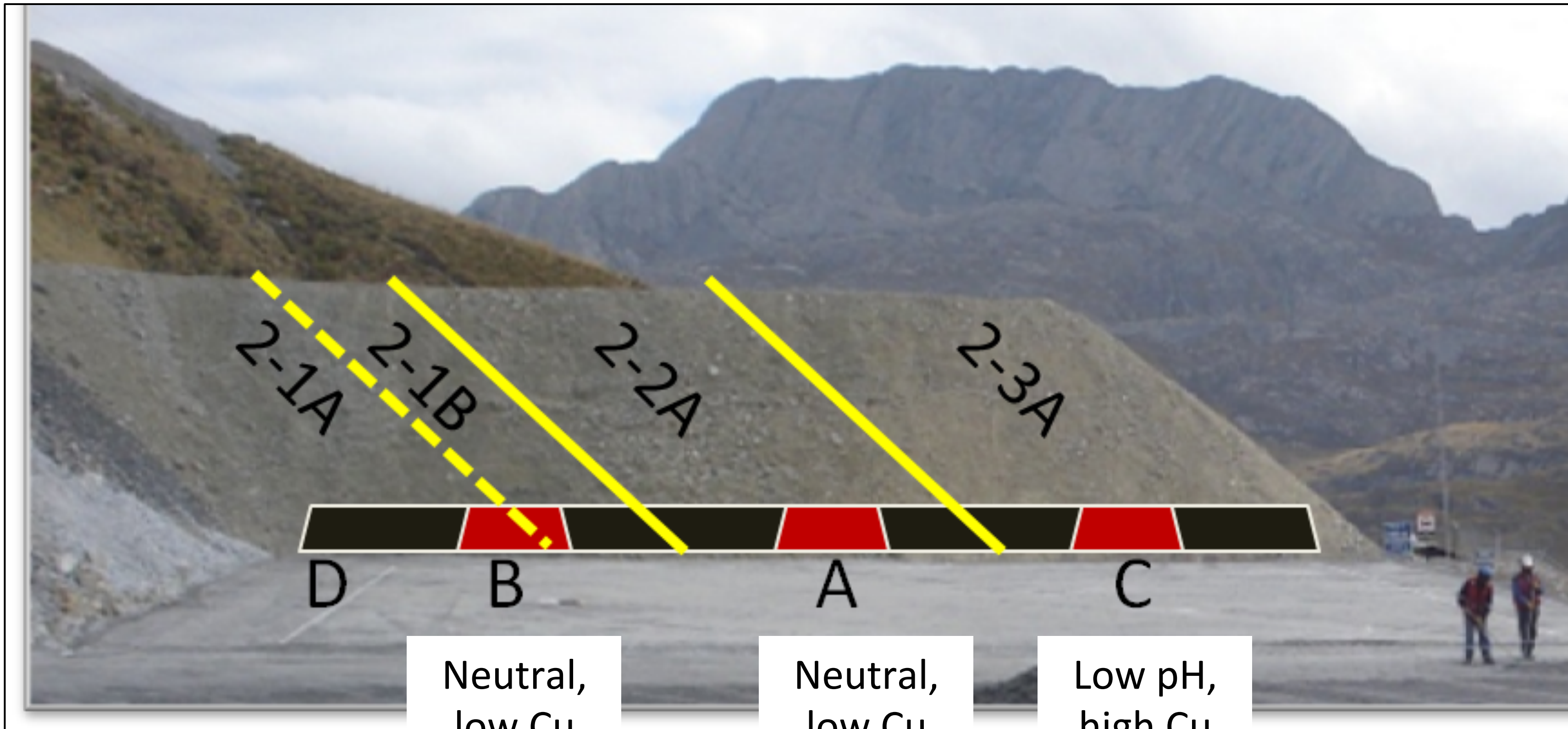
ANTAMINA WASTE ROCK STUDY

Lessons learned

- Mo in solution can be strongly attenuated by Pb to form wulfenite
- With sufficient contact time, Mo in solution *may be* attenuated in powellite ($CaMoO_4$)
- Management strategy: stack attenuating material below releasing material
- Sequence of encounter important
  - Capacity?
  - Passivation?
  - Channeling/preferential flow?

ANTAMINA WASTE ROCK STUDY

Mixing and rapid transition



Neutral, low Cu drainage

Neutral, low Cu drainage

Low pH, high Cu drainage

ANTAMINA WASTE ROCK STUDY

Overview: Rapid geochemical transition

- During a two-month period:
  - pH dropped
    - pH 7.7 → pH 6.4
  - Cu increased
    - 0.01 mg/L → 67.0 mg/L
  - Zn increased
    - 5.9 mg/L → 41.9 mg/L
  - Accumulation of predominantly amorphous precipitate

ANTAMINA

NSERC CRSNG

Teck

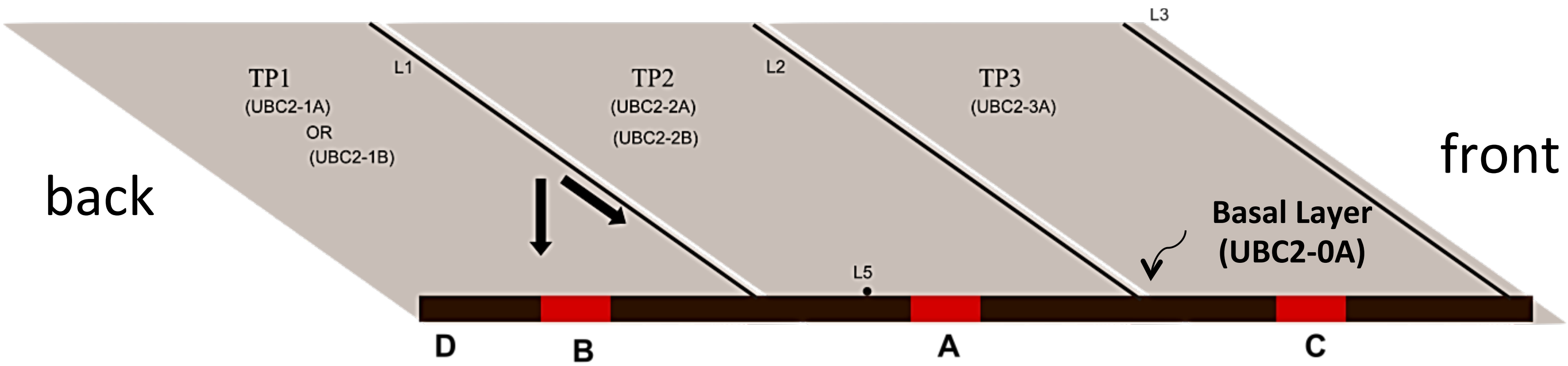
UBC

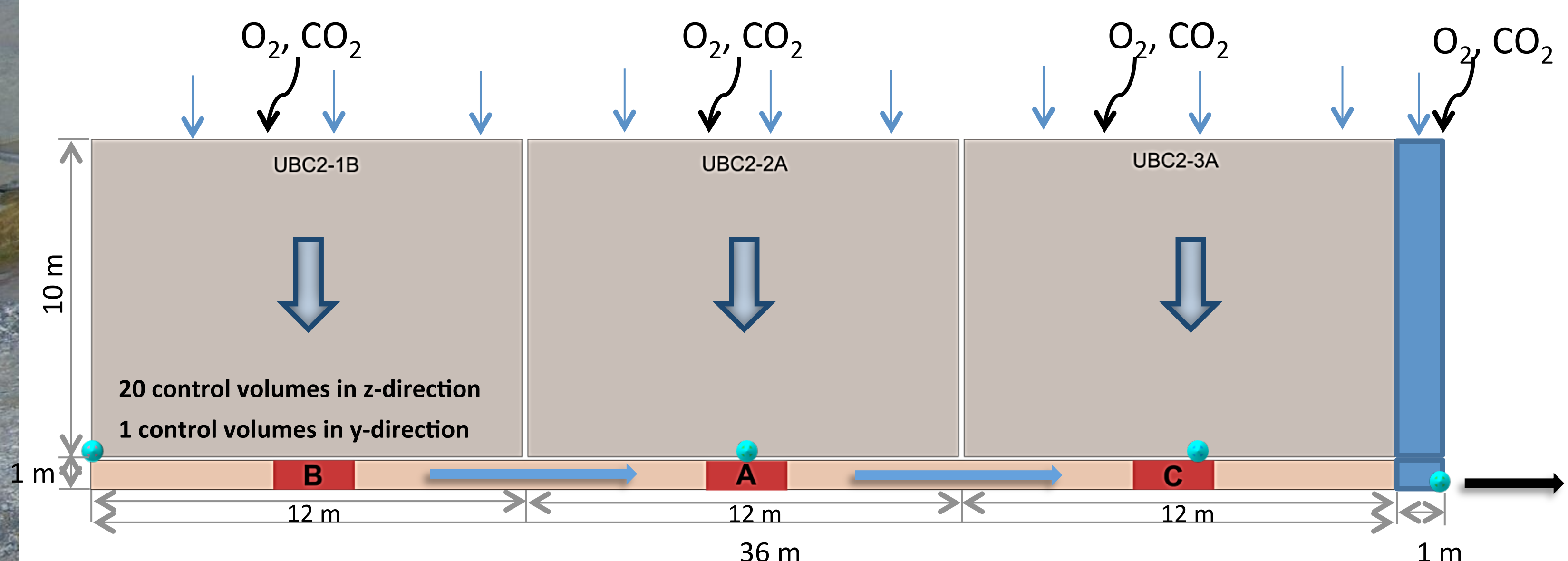
Models

George E. P. Box: "All models are wrong but some are useful."
Aristotle: "It is the mark of an educated mind to rest satisfied with the degree of precision which the nature of the subject admits and not to seek exactness where only an approximation is possible."

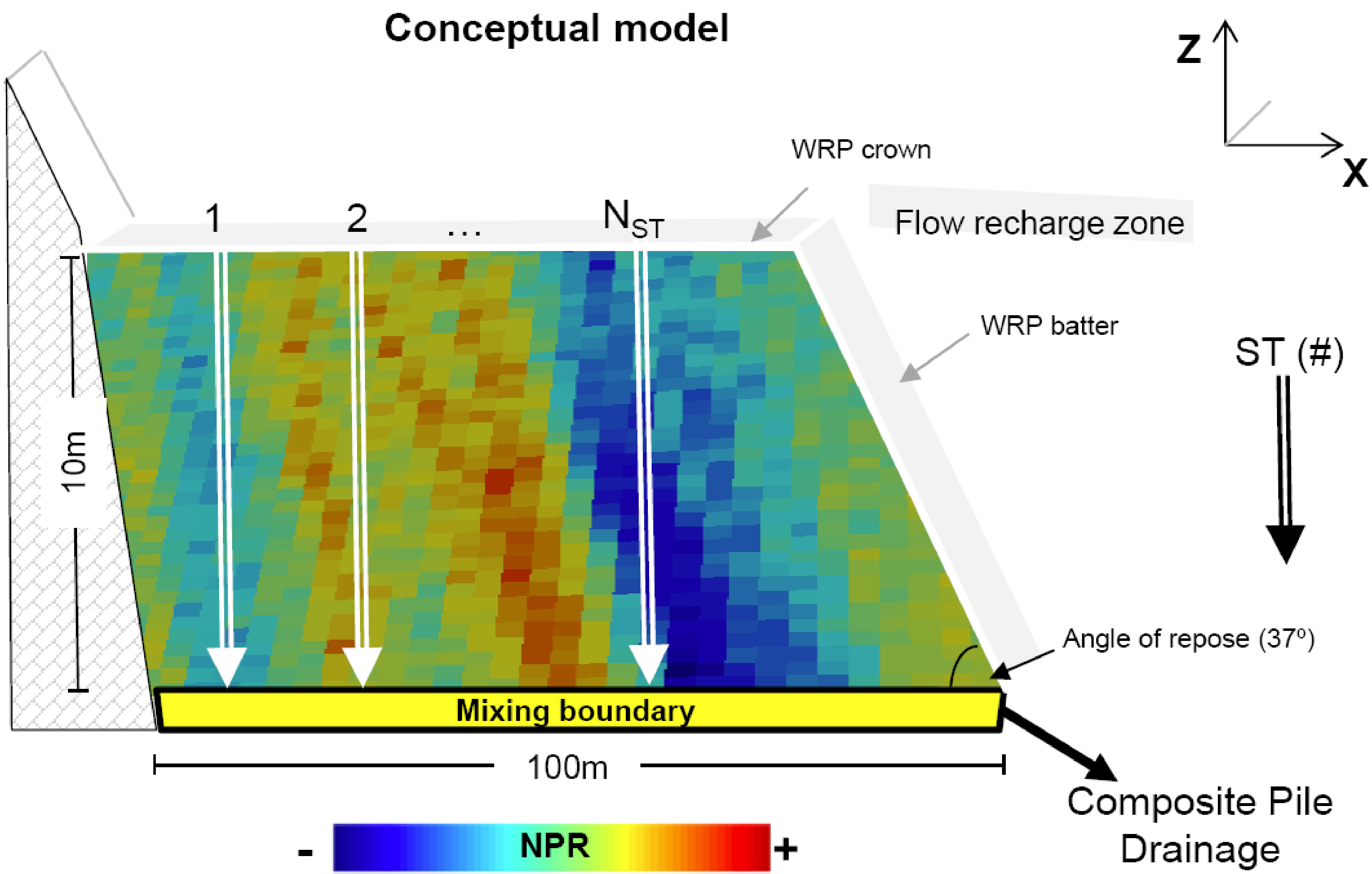
➔Model should be **fit for its purpose**

Conceptual Model



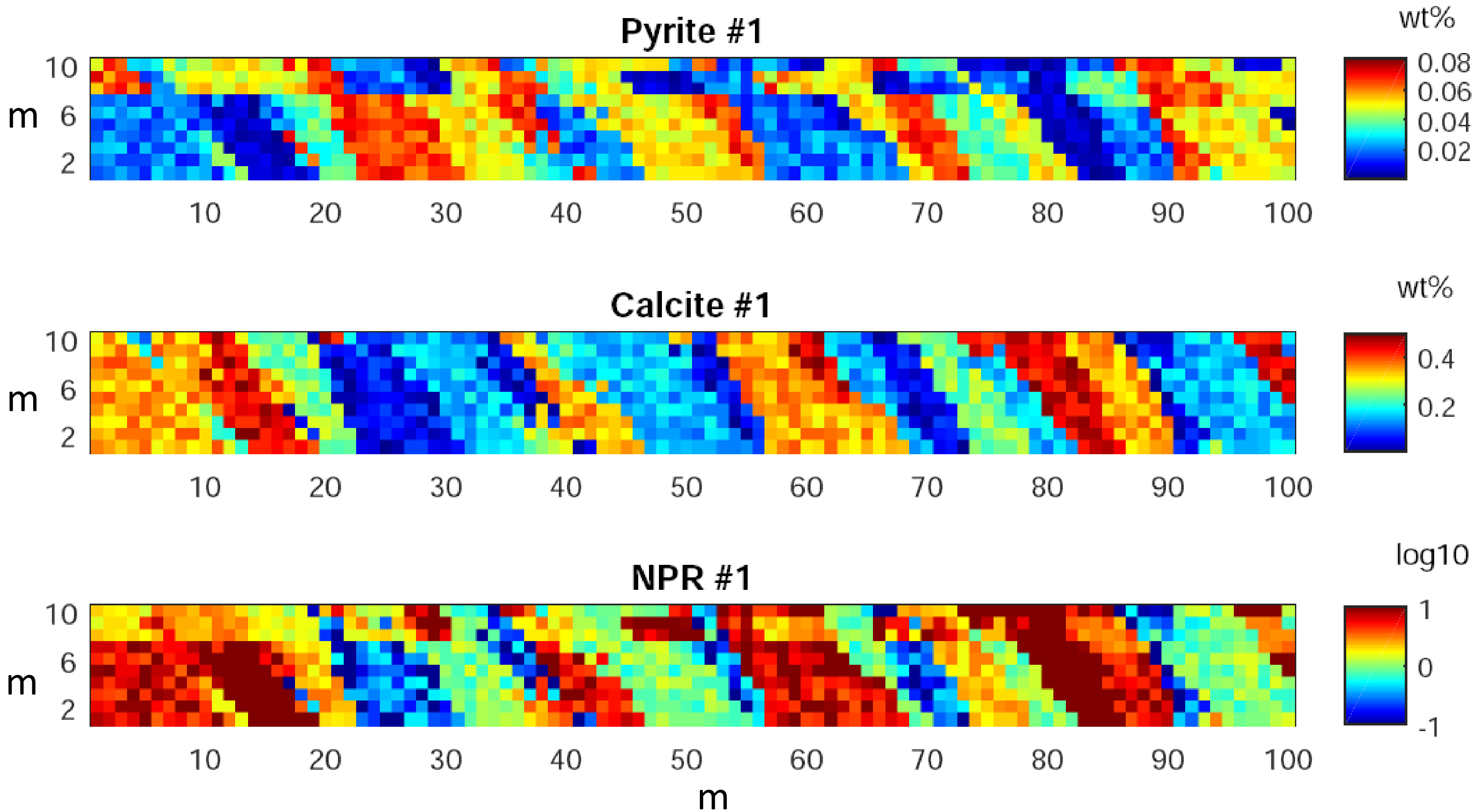


Probabilistic stream-tube model



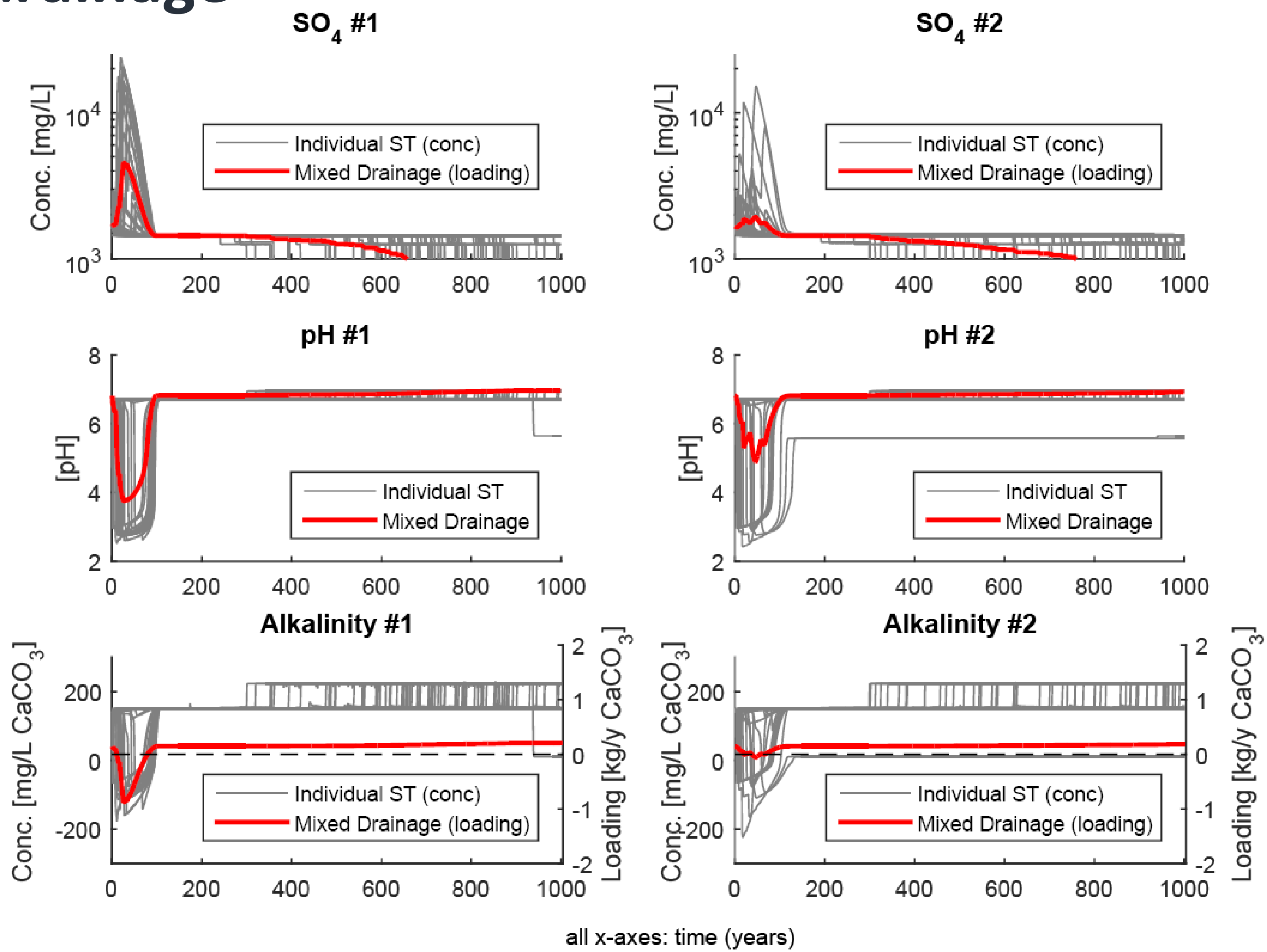
Probabilistic stream-tube model

One possible distribution of materials in pile (realization)



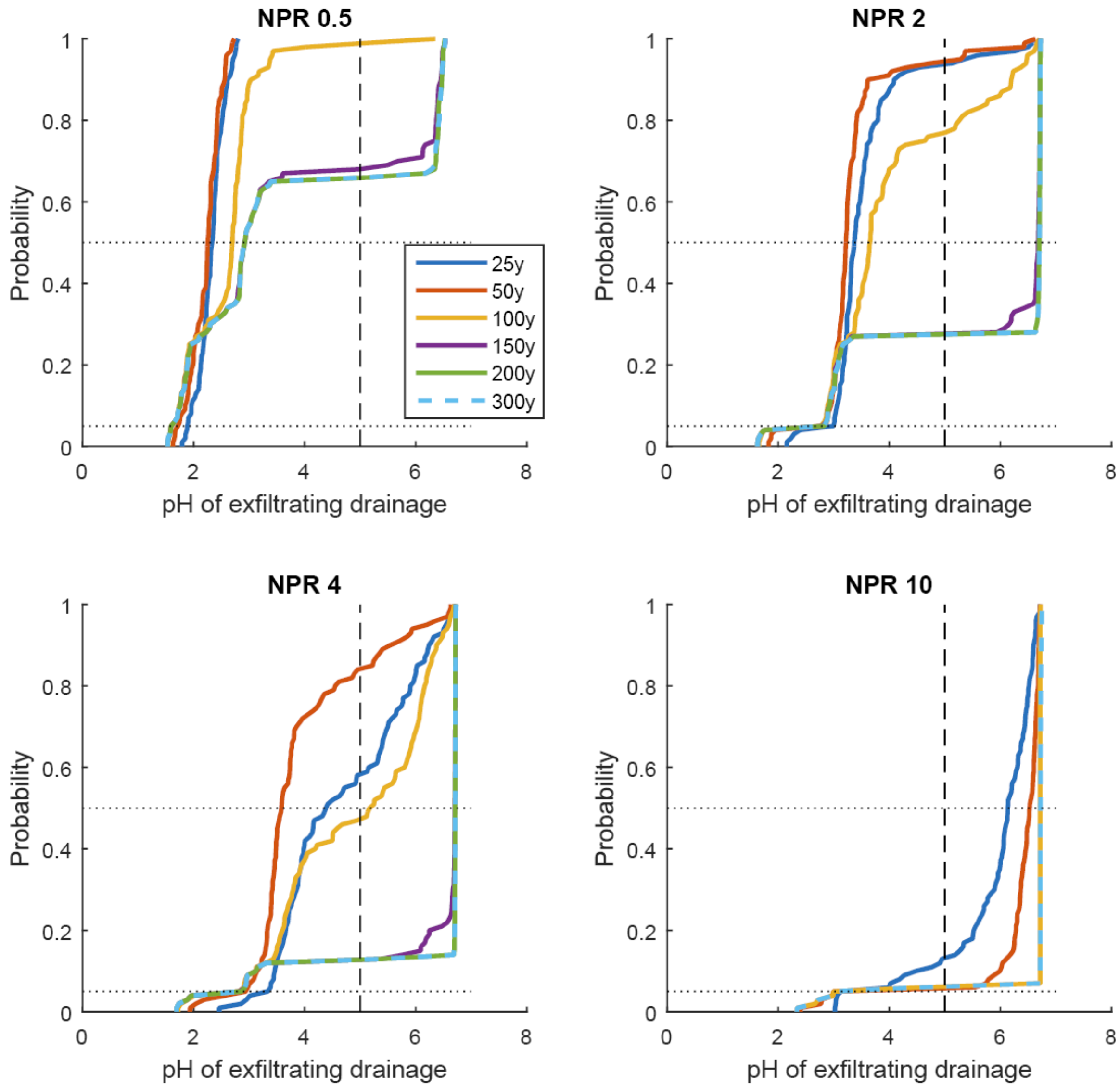
ANTAMINA WASTE ROCK STUDY

Prediction of stream-tube and total-pile drainage



Bulk neutralization potential ratio versus probability of drainage pH at different times

ANTAMINA WASTE ROCK STUDY



What bulk NPR provides good-quality drainage most of the time?

Lessons learned

- Independent vertical flow paths with mixing at bottom
- Stream-tube assessment of effects of heterogeneity

Full-scale

- Mixing at capillary breaks (traffic surfaces) and bottom of pile
- Effects of traffic surfaces, heat and gas: ongoing

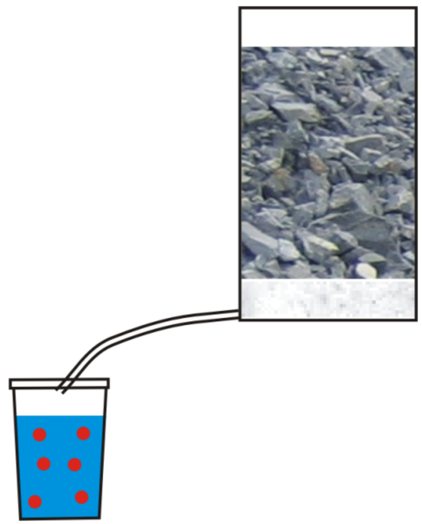
Rates: intrinsic versus apparent

Intrinsic	Apparent
rate at which mineral is chemically transformed by reaction	rate at which mass is released into solution and transported out of system

Kinetic & field barrels, pile drainage→ apparent rates

Oxygen consumption → intrinsic rates

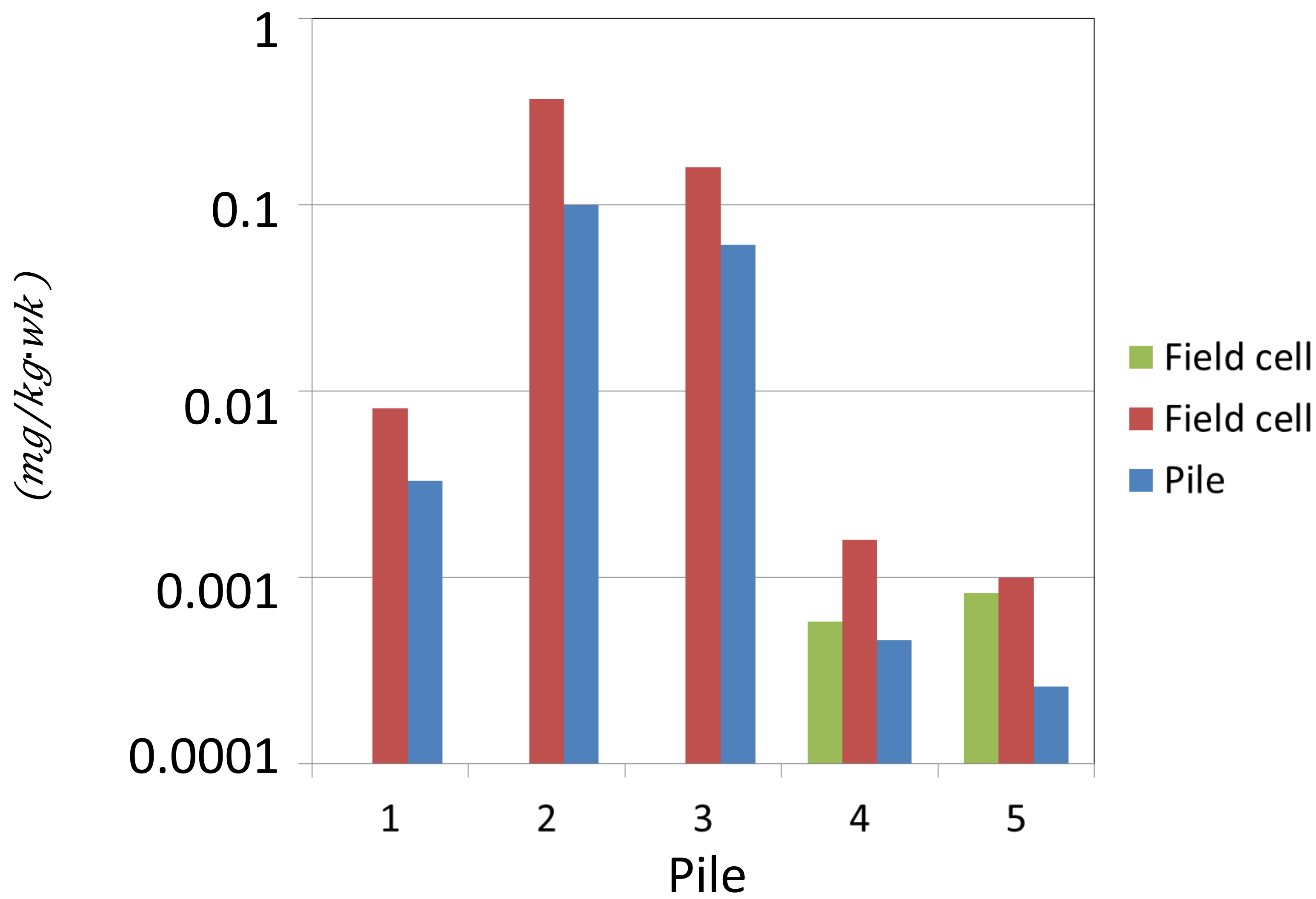
Computing rates



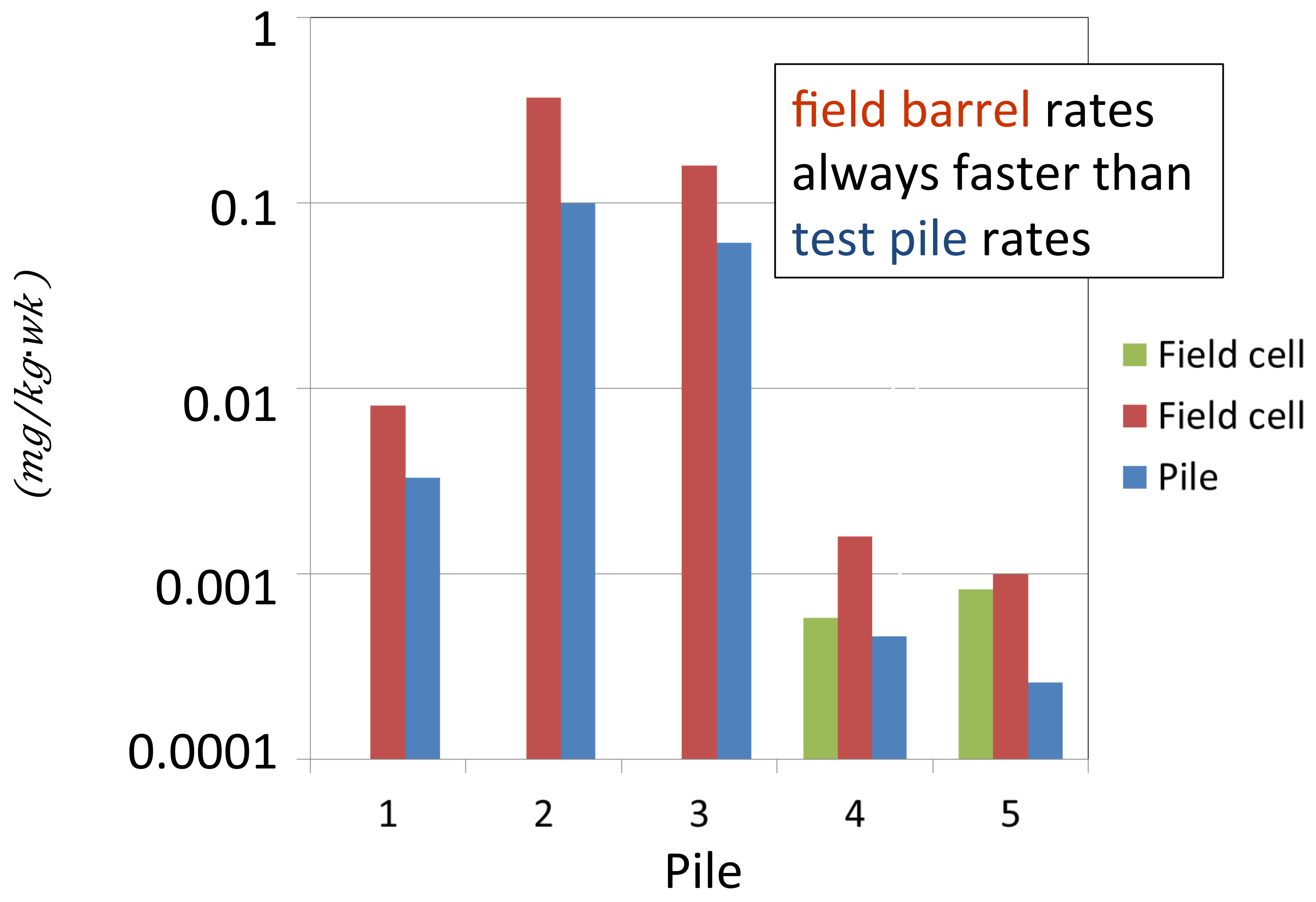
Units $(mg/kg{\cdot}wk)$

$$\frac{\text{Mass transported out of system in water in time } \Delta t}{\text{Mass of source rock} \times \Delta t}$$

Apparent Zn rates: field barrels and piles



Apparent Zn rates: field cells and piles



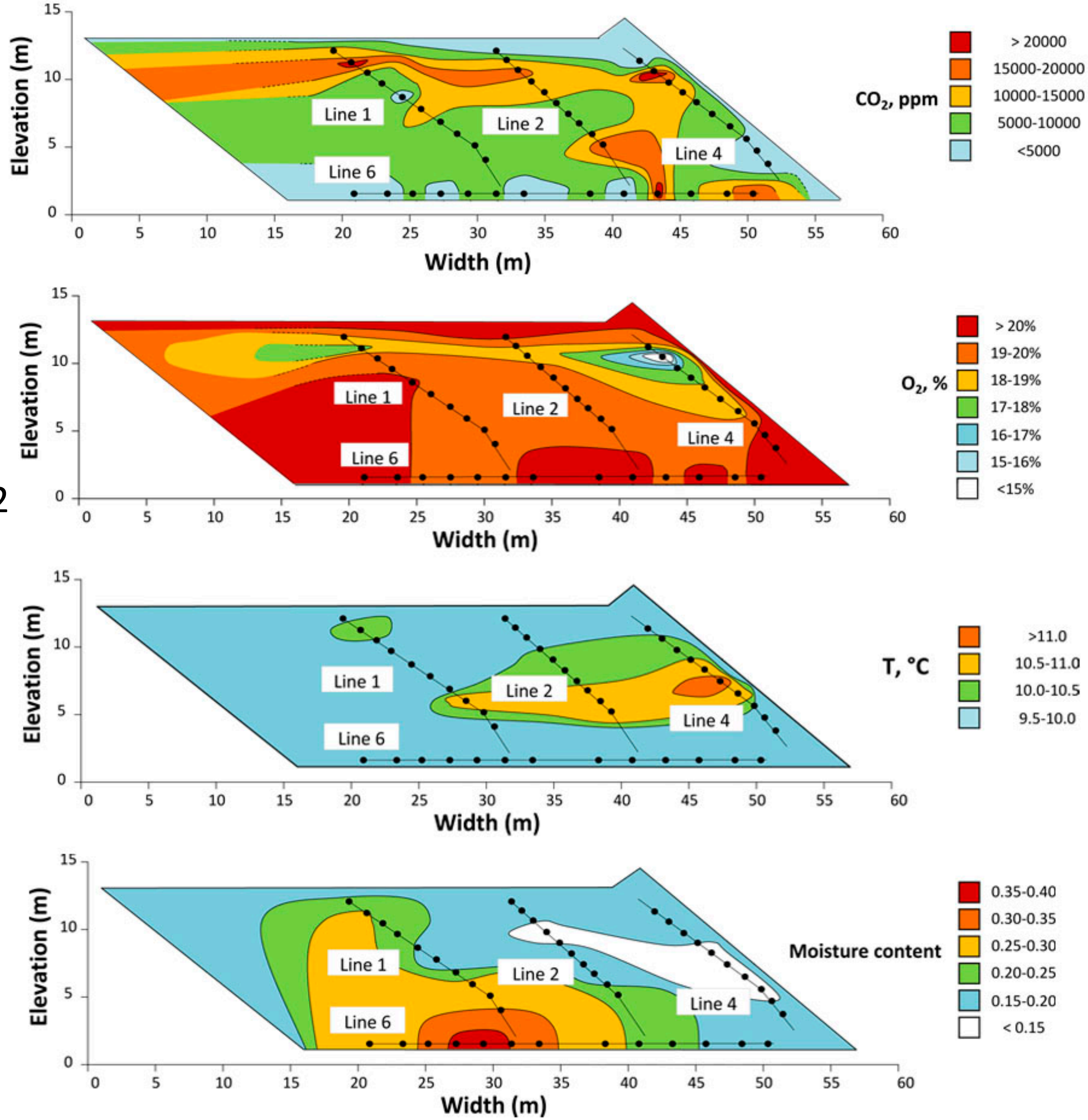
Scale effect: Cu

Location	$Field\ barrel\ rate / Pile\ rate$
Pile 1	36
Pile 2	49
Pile 3	15
Pile 4: type B	5.6
Pile 4: type C	37
Pile 5: type A	436
Pile 5: type C	166

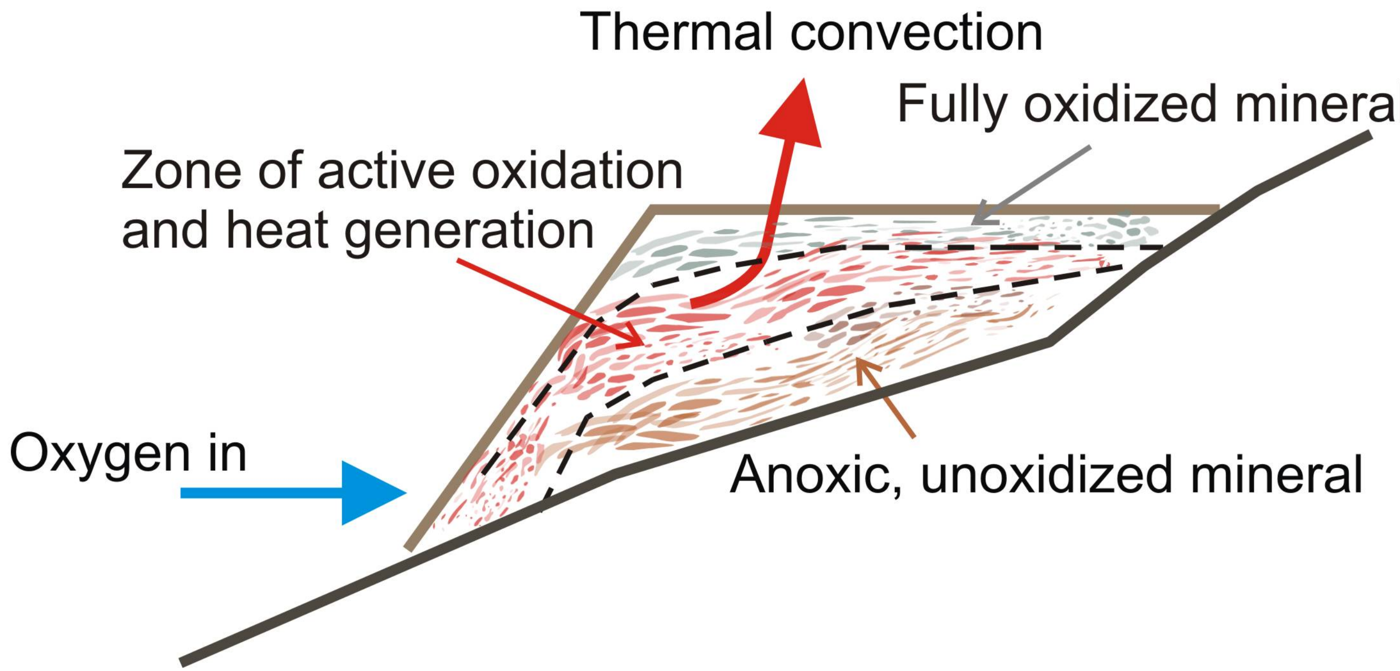
Pile 2

Oxygen depletion

Heat & CO_2 production



Conceptual model: Oxygen transport effects



Less oxidation than under fully aerobic conditions

Lessons learned

- Distinct rates determined from field barrels and experimental piles
- Value of lab-scale rates?
- Experimental – pile scale to full-scale-pile scale
  - Heat could increase rates
  - Gas transport limitations could decrease rates
  - Flow channeling could decrease release rates.


ANTAMINA
Celedonio Aranda
Bevin Harrison
Roberto Manrique
Antonio Mendoza
Michael Sanchez
Teck
Randy Blaskovich
Stephane Brienne
Henri Letient
Danny Bay
Sharon Blackmore
Mike Conlan
Juan Carlos Corazao
John Dockrey
Charlene Haupt
Trevor Hirsche
Mehrnoush Javadi
Laura Laurenzi
Matthew Lindsay
Maria Eliana Lorca
Daniele Pedretti
Juan Perez-Licera
Holly Peterson
Elliott Skierszkan
Melanie St-Arnault
Olga Singurindy
Pablo Urrutia
Bern Klein
Uli Mayer
Leslie Smith
Ward Wilson
Roger Beckie
UNIVERSITY OF ALBERTA
NSERC CRSNG
UBC
BUCYRUS