

# MINE WASTE GEOCHEMISTRY FOR ENGINEERS



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# Content

- ARD basics
- Design cases for discussion
  - KCB Case Studies and published KCB papers that provide more detail throughout presentation
  - All indicated with \* (reference list provided with slides)



# What is Acid Mine Drainage?

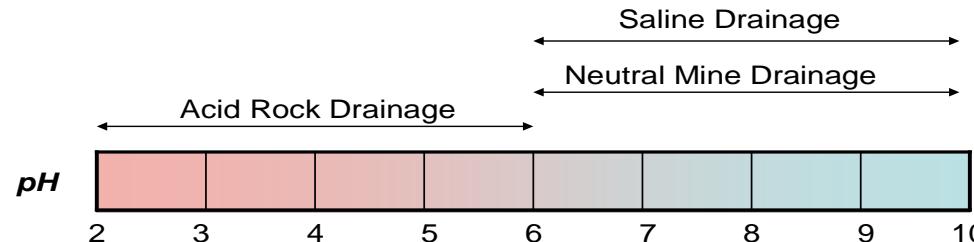
- Acid drainage is a consequence of the oxidation of sulphide minerals and the transport of reaction products by water
- In general : Acidic waters with high dissolved metals and sulphates emanating from sources associated with mining
- Consequences depend on the source material, geochemical conditions and receiving environment
- Acid drainage is one end member of the process
  - Can also be neutral with high salt content



# Definitions (from GARD GuideINAP\*)

## Types of Drainage Produced by Sulphide Mineral Oxidation

***Typical relation to drainage pH:***



***Typical drainage characteristics:***

Acid Rock Drainage:

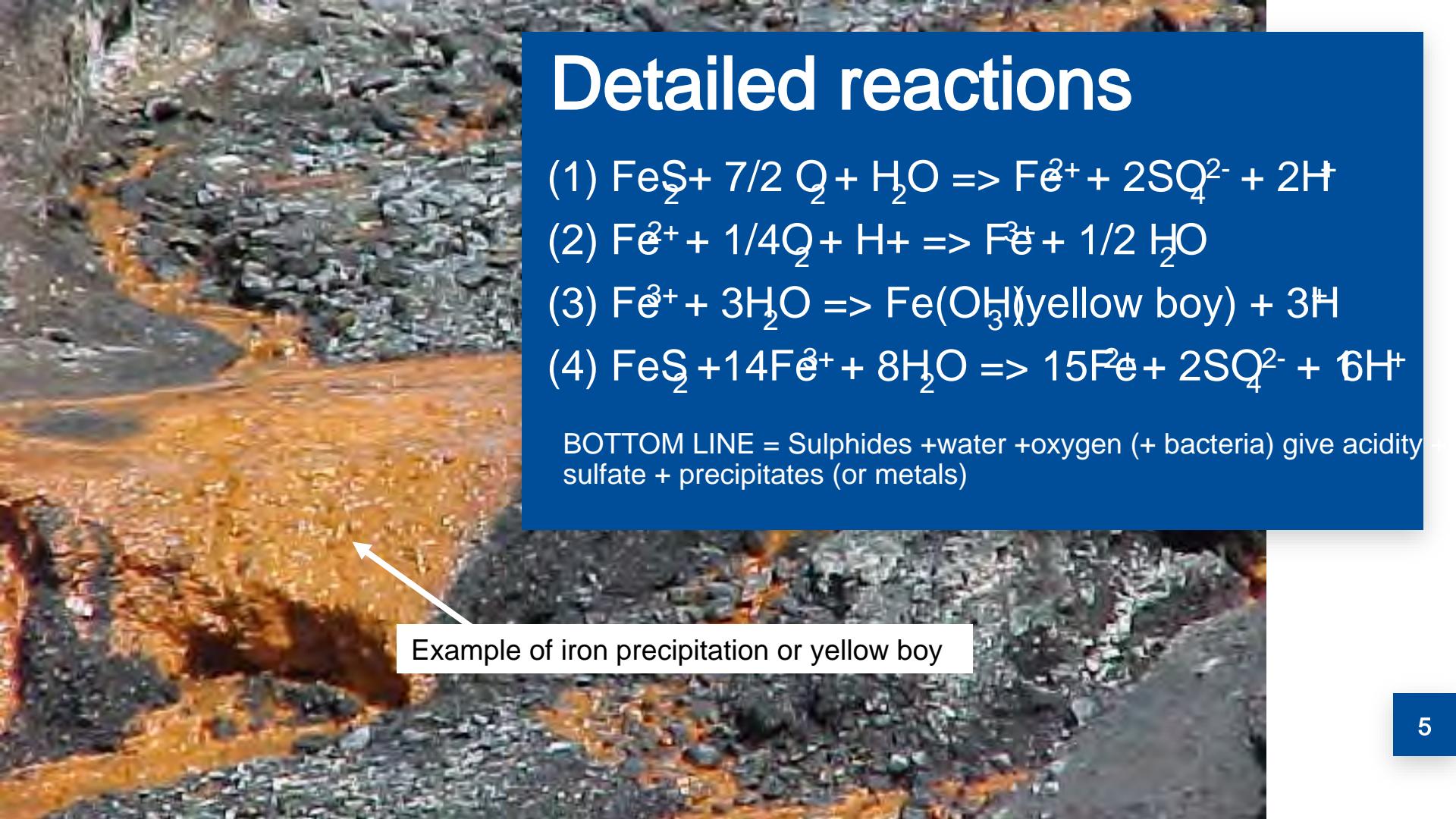
- acidic pH
- moderate to elevated heavy metals
- elevated sulphate

Neutral Mine Drainage:

- near neutral to alkaline pH
- low to moderate heavy metals. May have elevated zinc and cadmium.
- low to moderate sulphate

Saline Drainage:

- neutral to alkaline pH
- low heavy metals. May have moderate iron.
- moderate sulphate and calcium



# Detailed reactions

- (1)  $\text{FeS}_2 + \frac{7}{2} \text{O}_2 + \text{H}_2\text{O} \Rightarrow \text{Fe}^{2+} + 2\text{SO}_4^{2-} + 2\text{H}^+$
- (2)  $\text{Fe}^{2+} + \frac{1}{4}\text{O}_2 + \text{H}^+ \Rightarrow \text{Fe}^{3+} + \frac{1}{2}\text{H}_2\text{O}$
- (3)  $\text{Fe}^{3+} + 3\text{H}_2\text{O} \Rightarrow \text{Fe}(\text{OH})_3$  (yellow boy) + 3H<sup>+</sup>
- (4)  $\text{FeS}_2 + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} \Rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 6\text{H}^+$

BOTTOM LINE = Sulphides +water +oxygen (+ bacteria) give acidity + sulfate + precipitates (or metals)

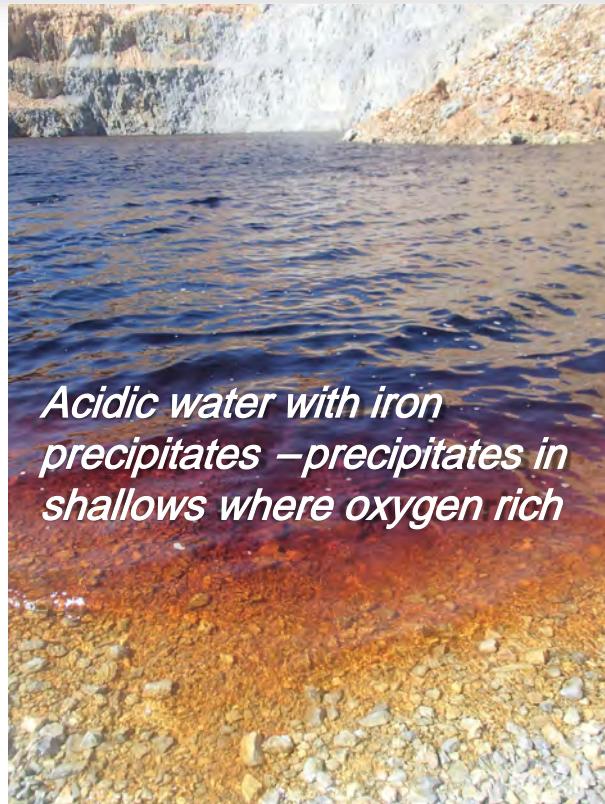
Example of iron precipitation or yellow boy



## Basic recipe (#1)

- Sulphide minerals (often pyrite) react with oxygen and water (with some help from microbes) to generate acidity and sulphate and iron (and some heat)
- Neutralisation mostly from carbonate minerals
- Associated metals/resultant pH and the load largely = consequence
- Reaction products often form precipitates

# Abandoned Pit (Australia)



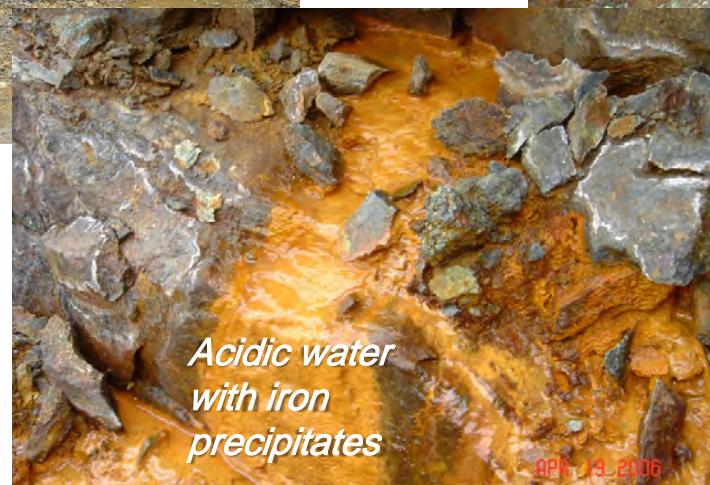
*Acidic water with iron precipitates – precipitates in shallows where oxygen rich*

pH 1.5!



*Acidic water*

# Example from a metal mine





# Old TSF in dry climate





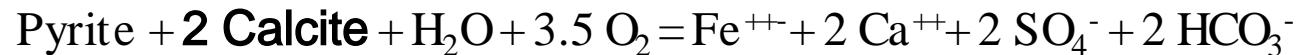
# Old TSF in dry climate



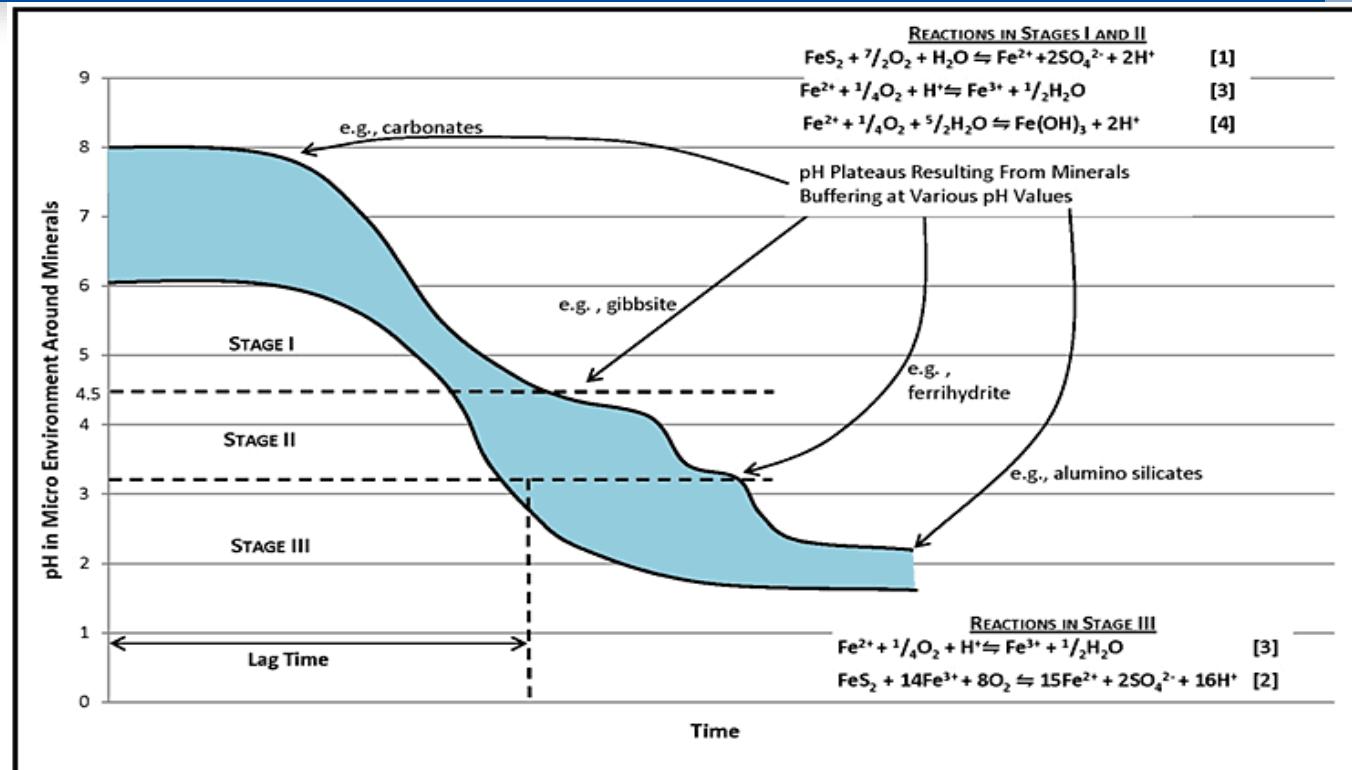


# Neutralisation of acidity

- As the AMD process proceeds coexisting buffering mechanisms can prevent drops in the pH
- The sequence of this is usually alkalinity in the water, followed by carbonate minerals, followed by hydroxides (Al and Fe) and then by silicate dissolution
- Usually carbonate minerals such as calcite and dolomite are the most important



# Generalised sequence\*



Stages in the Formation of ARD (after Broughton and Robertson, 1992)

# Not enough neutralising minerals

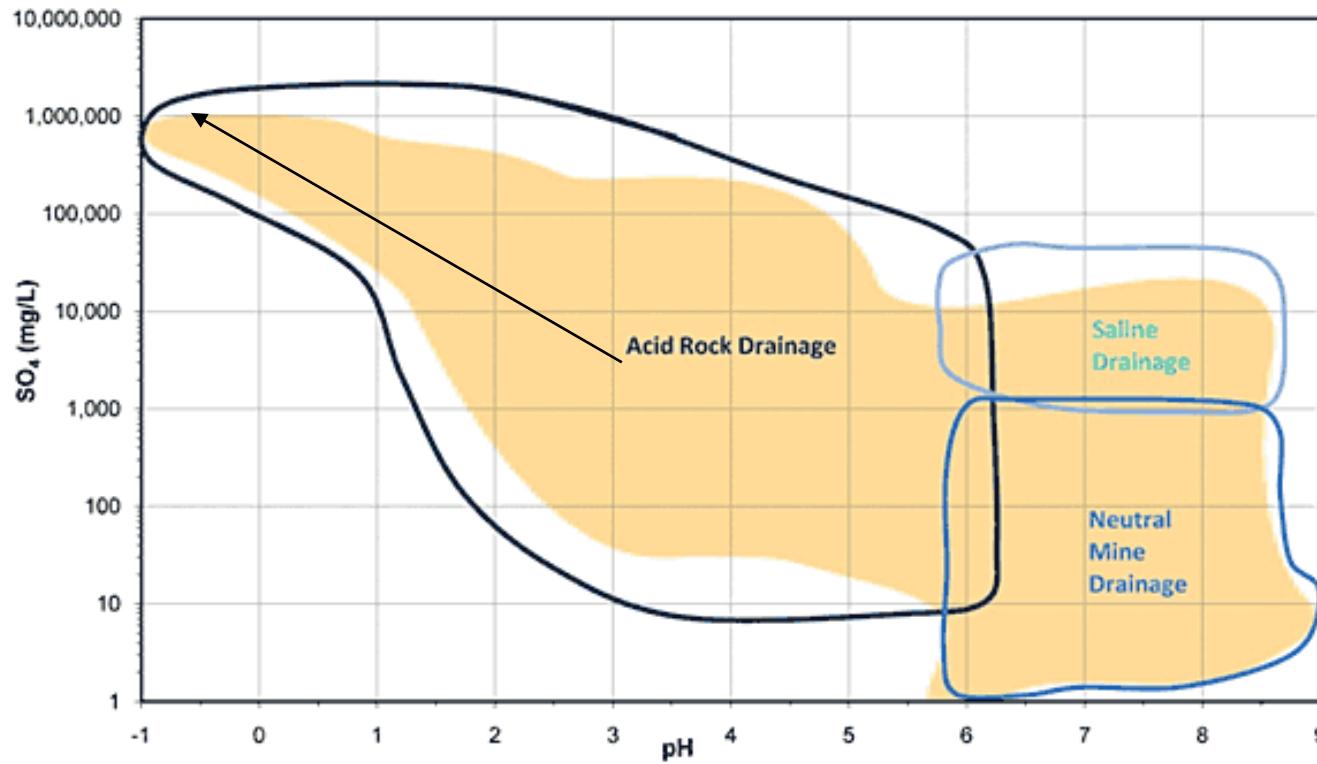


*Acidic < pH 3 water*



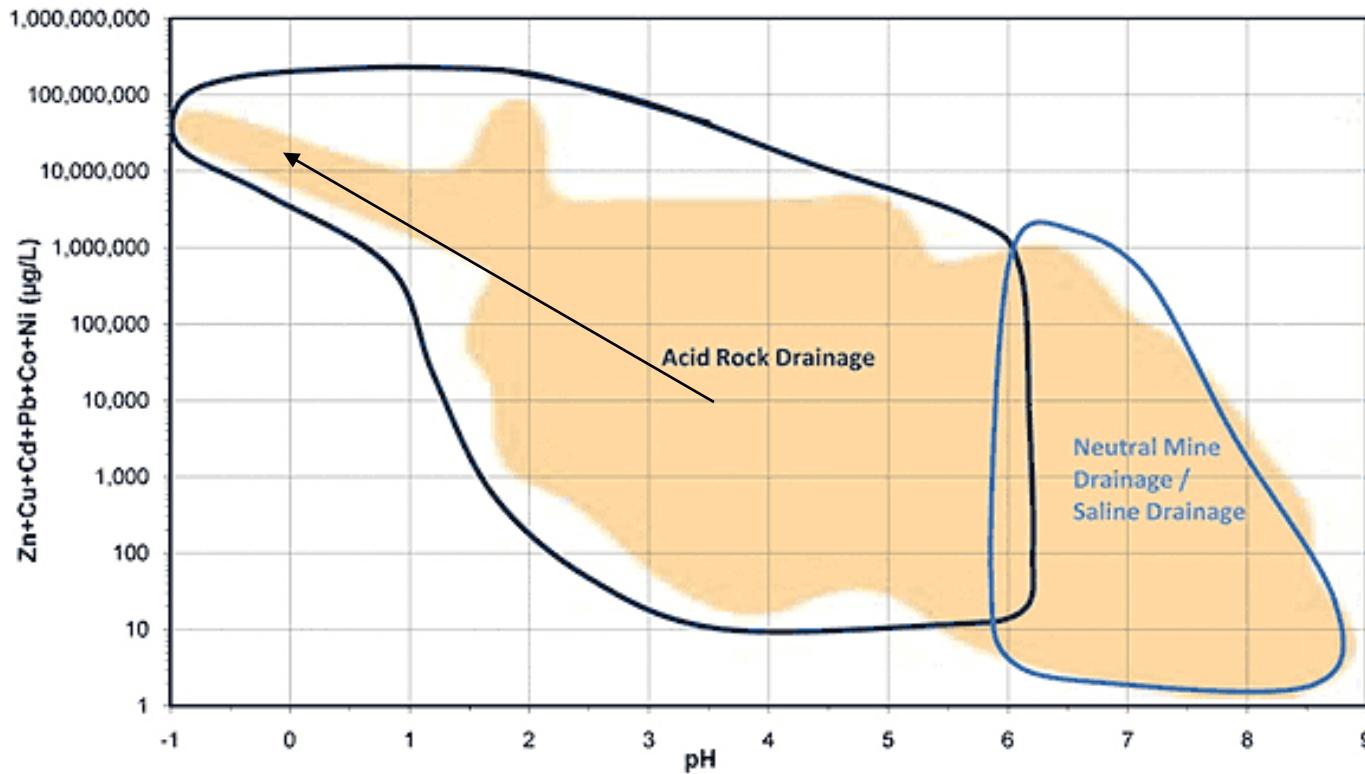
# AMD vs NMD vs SMD\*

Sulphate and salinity



# AMD vs NMD vs SMD\*

Metals





## Neutral drainage and saline drainage

- Acid/non-acid is often the focus
  - Low pH increases reactivity and metal release
- But.....
- Just because it is not current acidic ≠ the process is not occurring
- In addition to salinity, under neutral conditions other metals/metalloids of concern like As, Mo or Se can still be released

## Example at a WRD (neutral)



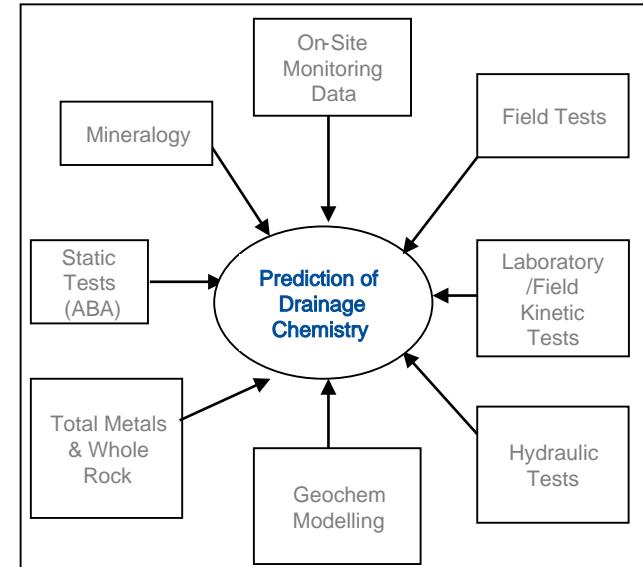


# GEOCHEMICAL CHARACTERISATION



# What do we need to do to predict mine water chemistry?

- Several different tools are available, depending on the needs to predict acid generation
- Combination needed for confidence in results
- Which tools to use depends on what we need to understand



**Bottom Line:** Several tools and supporting data needed to predict mine water chemistry



# Prediction Method Classes

- Static Methods
- Kinetic Methods
- Geochemical Modelling
- Field Methodologies



## Which tools to use when

- Static tests determine the balance between acid generation potential and neutralising potential
- DO NOT GIVE US RATES for these we need kinetic rates
- Usually combine all the data and conceptualisation in a hydrogeochemical model to predict water quality changes



# The most important considerations in prediction

- Clearly define your objectives
- Know the limitations
- Place the results in context with a conceptual geochemical model
- Use more than several methods to have confidence in the results



# Kinetic Tests: Columns & Humidity Cells\*





# DESIGN CONSIDERATIONS 1

## Using Water to limit Oxygen



## Limiting reactivity by eliminating oxygen

- Placing waste under water
  - a) Specific facilities (storage ponds)
  - b) Submerging waste deep in permanent pit lakes
  - c) Keeping tailings at very high moisture content



## Basic recipe (#2)

- Sulphide minerals (often pyrite) react with ~~oxygen~~ and water (with some help from microbes) ~~to generate acidity and sulphate and iron (and some heat)~~
- Neutralisation mostly from carbonate minerals
- Associated metals/resultant pH and the load largely = consequence
- Reaction products often form precipitates



## Storing high sulphide waste under water

- Several case studies
- High rainfall environments
- Designs to keep several metres of water above waste
- Water acts to prevent oxygen



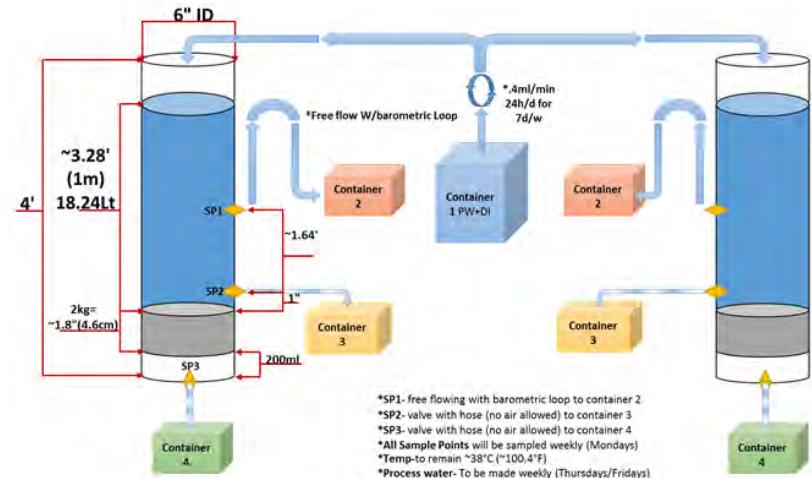
S. Miller (2014)

Bige Dredge sand stockpile showing a Pcon disposal cell in the background (water filled pond).



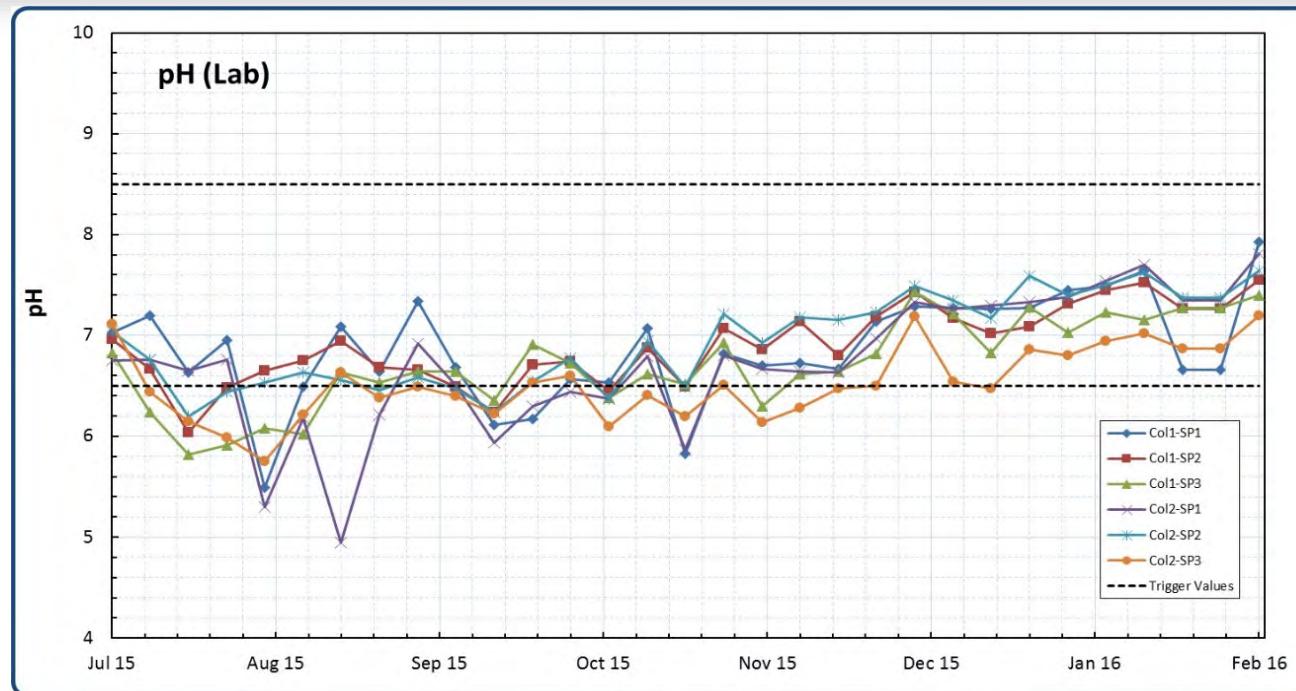
# Example of experimental testing of submergence

- Long-term kinetic tests (several years)
- Submerge the highly reactive pyritic waste
- Monitor the results
  - Particularly sulphate and pH



Experimental set up:  
Samples remain submerged

# Example results from submerged columns



pH remains neutral over several years of testing



# TSF example in wet tropical environment

- Closure plan concept for HV TSF 1
  - See recent KCB webinar by Mark Rynhoud ([www.klohn.com/webinars](http://www.klohn.com/webinars))
- Balance between geotechnical requirements and geochemical considerations
- Geotechnically more stable with no pond
- Geochemically less reactive if tailings have no oxygen





## Proposed closure solution

- At closure remove and treat pond water
- Place coarse cover on final tailings surface
- Aims of cover:
  - Protect tailings from erosion
  - Allow flow to be channelled by design
  - Allow sufficient rainfall to infiltrate so that tailings water content is high enough to limit oxygen in the tailings



# DESIGN CONSIDERATIONS 2

## Integrating geochemistry in decision-making and costs



## Linking geochemistry to water and waste management (operations /closure)\*

- Long-running water quality model development
  - Model used for planning, prediction, regulatory engagements and closure planning
  - Client uses the model planning and decision making
  - Decisions which consider geochemistry and water quality integral part of costing of alternatives #

# Recent article in AUSIMM journal 2019



# End Goal: Fully functional WQ models for decision making, planning and assessment\*

*Antamina Mine Operational Water Quality and Water Balance Model V 2.35*

**Model Setup**  
*(Configuración del Modelo)*

*Simulation Runtime Settings*  
*(Configuración de la simulación)*

*Mine Scheduling Page*  
*(Entradas página principal)*

*Waste Rock Dump Settings*  
*(Configuración del Botadero)*

*TSF Settings*  
*(Establecer las condiciones climáticas)*

*EIA, SWMS, and Treatment Settings*  
()

*Diversion System Settings*  
*(Configuración del sistema de devisión de aguas)*

*Set climate conditions*  
*(Establecer las condiciones climáticas)*

*Initial water Quality*  
()

**Treatment Controls**

**Fast Access Switches**

**Model Outputs**  
*(Resultado del Modelo)*

*Tailings pond conditions*  
*(Condiciones de la poza de relaves)*

*Freshwater Storage Results*  
*(Condiciones de las Pozas)*

*Waste Rock Dump Results*  
*(Condiciones de la botadero)*

*Water Quality*  
*(Calidad del Agua)*

*Flow Results*  
*(Condiciones hidrológicas)*

*Compliance Point Water Quality*  
()

*Quebrada Antamina New Treatment Systems*  
()

**TSF**

**FW Stores**

**Dumps**

**WQ**

**Flows**

**Compliance WQ**

**Qda Antamina**

**User Inputs**

**User Manual**

**Run Model**

**Browse Model**

**Map**

**Visuals Dashboard**

**Exit/Salida**

Model dashboard that mine site uses



# Approach\*

- Create or link to operational water balance
- Model the geochemistry of each component separately
- Use waste schedule and static geochemical test results to define source terms
- Use kinetic geochemical testing to define expected rates
- Use monitoring record to define expected behavior and reasons for observations
- Compare model to field observations
- Include operational options and constraints
- **Use the model for planning, assessment, costing, closure**



# Geochemical Data Sources\*\*

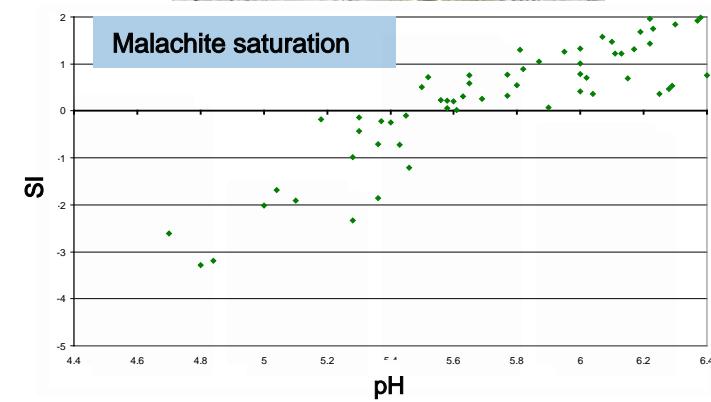
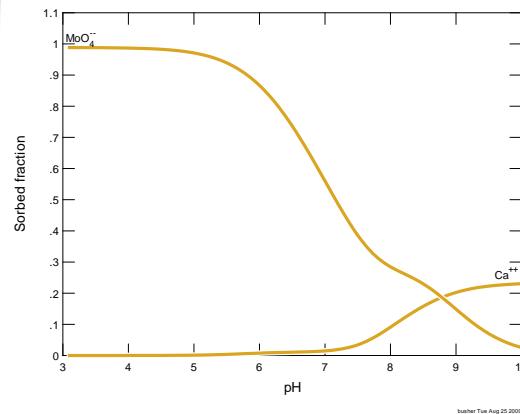
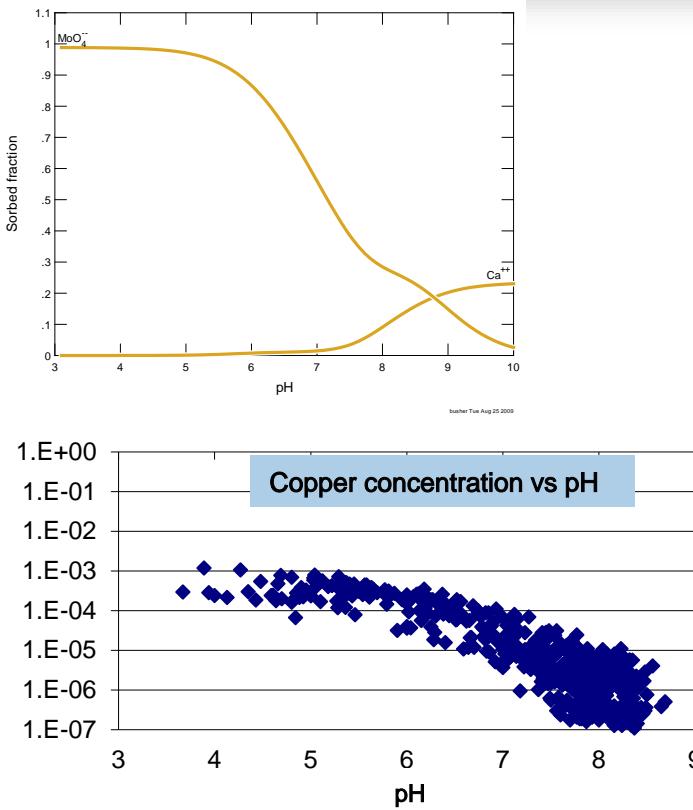
- Laboratory testing
  - Static testing
  - Humidity cells
  - Mineralogy
  - PSD
- Kinetic testing
  - Lab tests
  - Field cells
  - Field piles
- Field water quality monitoring records



# Deriving the Geochemistry



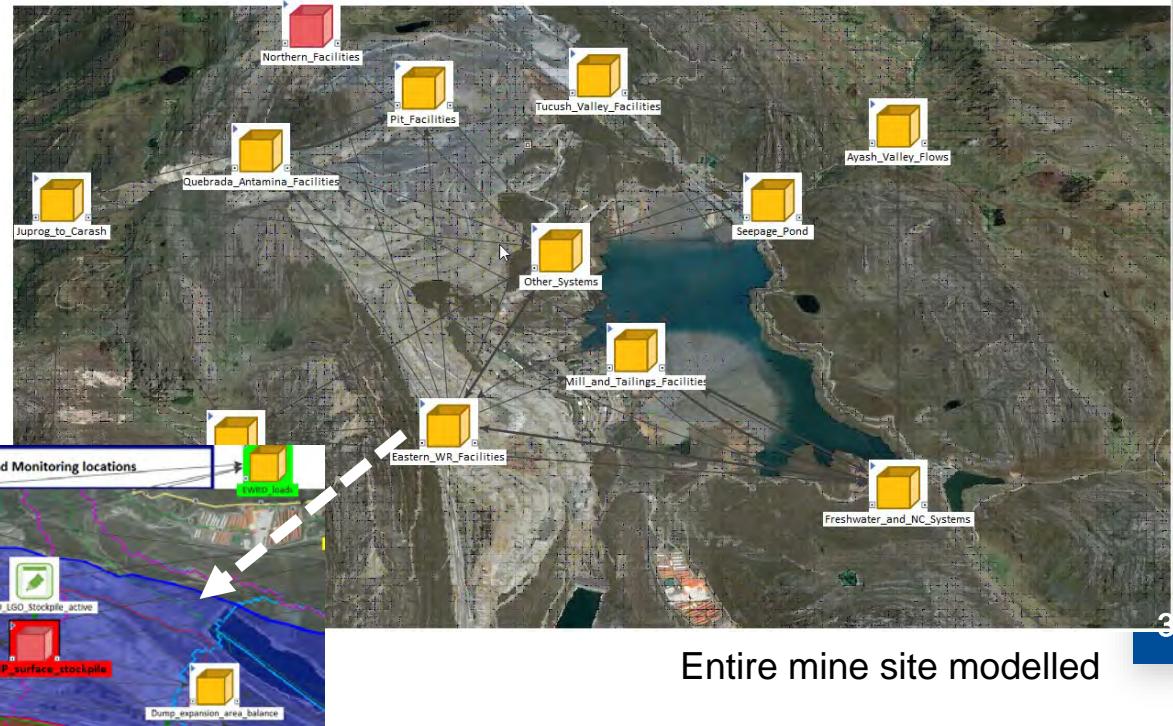
Copper Molar Concentration



# Integrated Water Balance and Water Quality Model



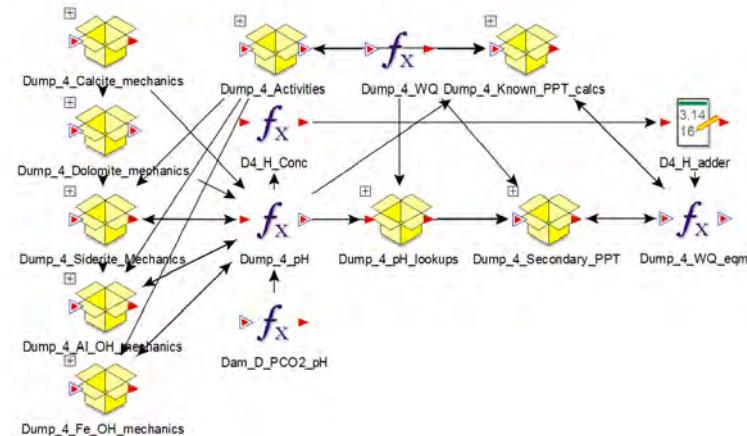
Antamina Integrated Water Balance and Water Quality Model Facilities Overview



Entire mine site modelled

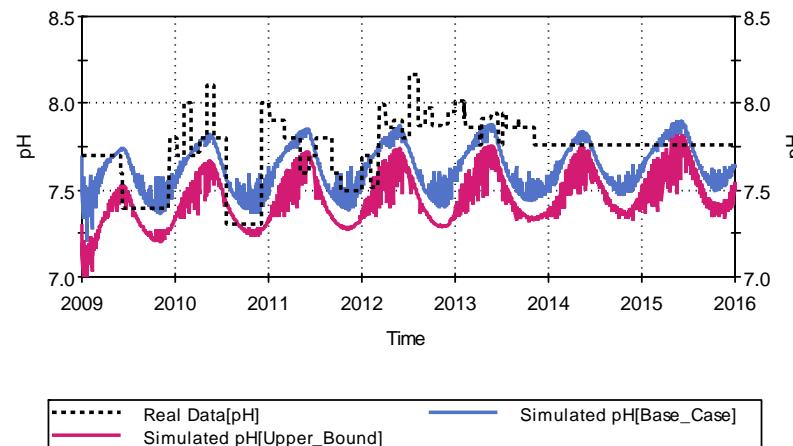
## Basic calculations occurring in each time step

- Flow
  - Loading
  - Mass balance
  - Acidity generated/Neutralization consumed
  - Corrections for non-ideality
  - pH determined (also as function of  $P_{CO_2}$ )
  - Secondary precipitation
  - pH-dependent solubility
  - Effects of Sorption
  - “Equilibrated” water quality transferred

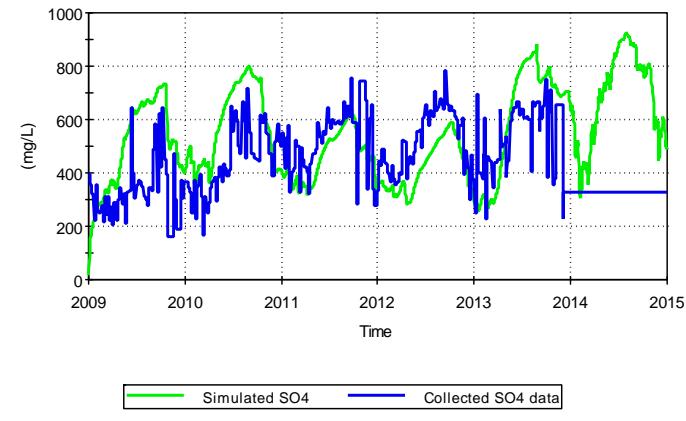


## Example of calculations

# Example of calibration (model vs real)



Sulfate comparison downstream of a waste rock dump

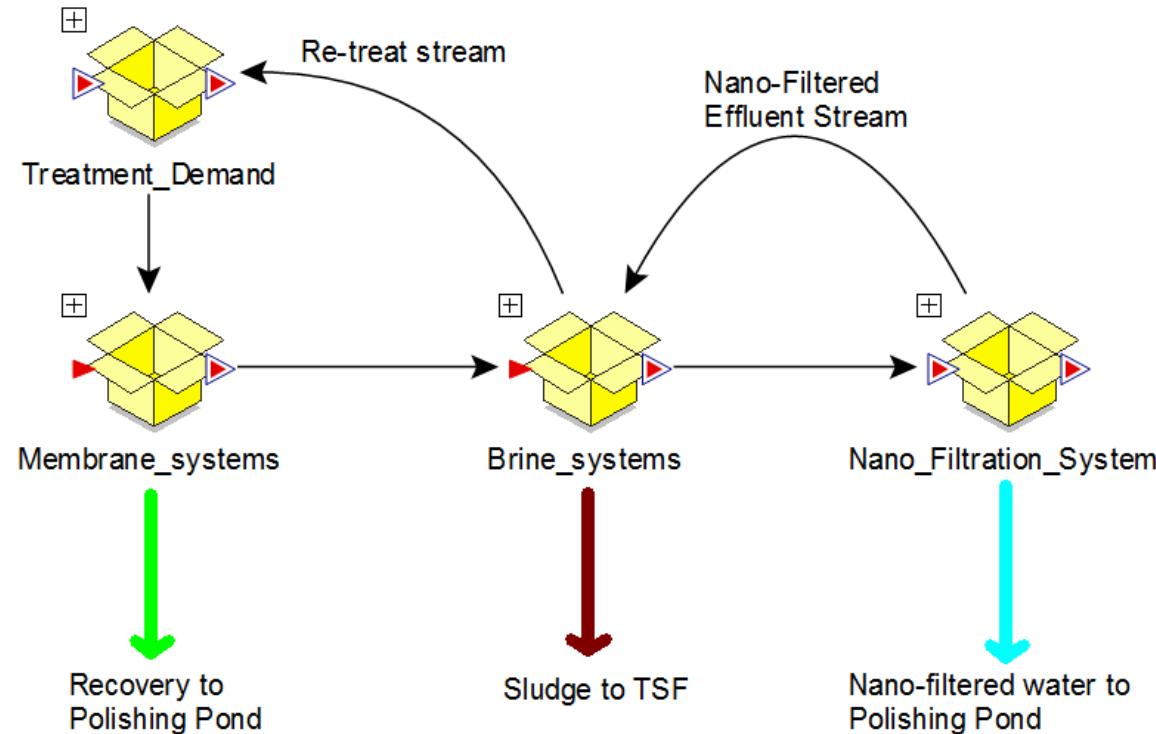


# Calibration Dashboard



Water Quality											
CO 28 Compariso n to Real WQ data	CO 42 Compariso n to Real WQ data	EST 02/03 Compariso n to Real WQ data	CO 44 Compariso n to Real WQ data	CO 16 Compariso n to Real WQ data	CO 13 Compariso n to Real WQ data	CO 21D Compariso n to Real WQ data	AN 25 Compariso n to Real WQ data	CO 22 Compariso n to Real WQ data	CO 24 Compariso n to Real WQ data	CO 37 Compariso n to Real WQ data	AN 24 Compariso n to Real WQ data
AI	AI	AI	AI	AI	AI	AI	AI	AI	AI	AI	AI
As	As	As	As	As	As	As	As	As	As	As	As
Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd
Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca
Cl	Cl	Cl	Cl	Cl	Cl	Cl	Cl	Cl	Cl	Cl	Cl
F	F	F	F	F	F	F	F	F	F	F	F
Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe
Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu
Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn
Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo
Pb	Pb	Pb	Pb	Pb	Pb	Pb	Pb	Pb	Pb	Pb	Pb
pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH
SO4	SO4	SO4	SO4	SO4	SO4	SO4	SO4	SO4	SO4	SO4	SO4
Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn
NH3	NH3	NH3	NH3	NH3	NH3	NH3	NH3	NH3	NH3	NH3	NH3
NO3	NO3	NO3	NO3	NO3	NO3	NO3	NO3	NO3	NO3	NO3	NO3
EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC
Na											
Alkalinity											

# Treatment system simulated





# Considerations for Design

- Enables system response simulations for a range of project stages and options
  - Multicriteria analysis for critical water quality drivers
  - Waste placement strategies
    - Reactivity (lift heights), covers (water/Q<sub>2</sub>)
    - Preferred locations
  - Water management options and implications
- Mine uses this to understand cost/benefit & environmental compliance risks



# DESIGN CONSIDERATIONS

## Waste rock placement & WRD design



## Basic recipe (#3)

- Sulphide minerals (often pyrite) react with oxygen and water (with some help from microbes) to generate acidity and sulphate and iron (and some heat)
- Neutralisation mostly from carbonate minerals
- Associated metals/resultant pH and the load largely = consequence

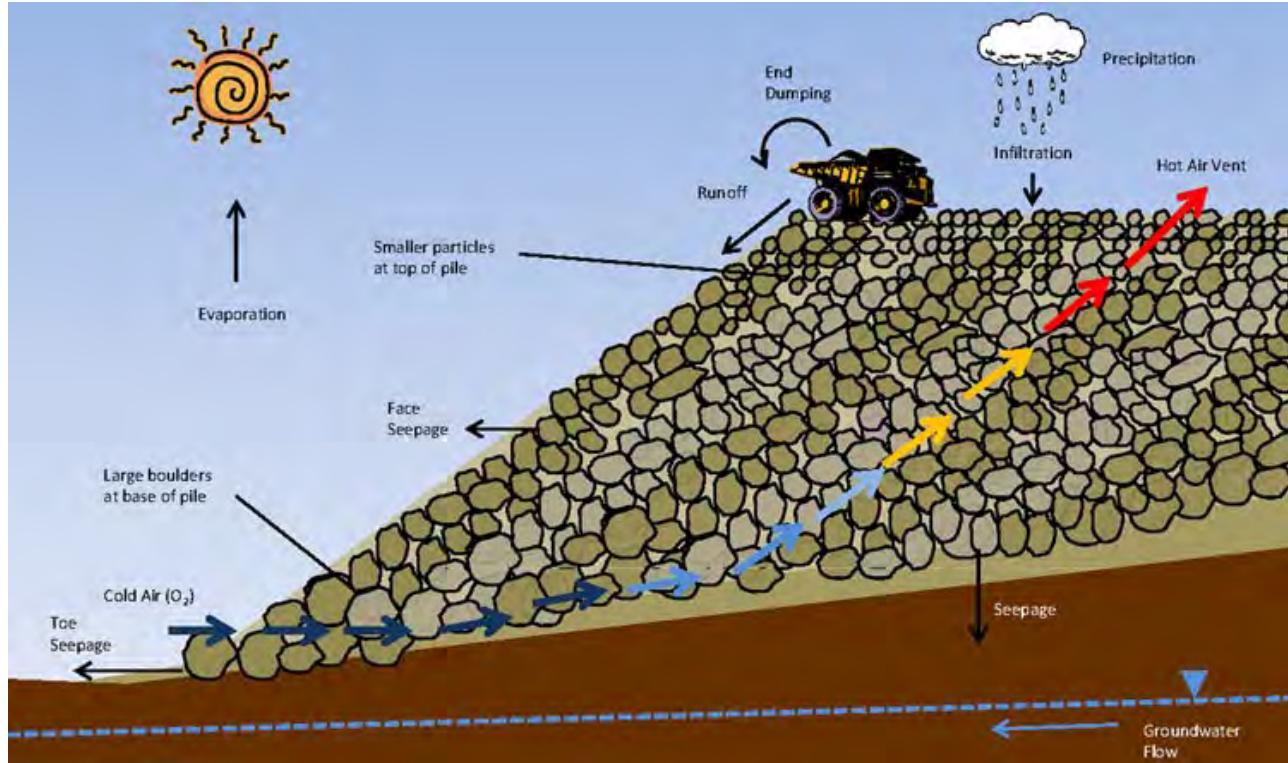


# Waste Rock

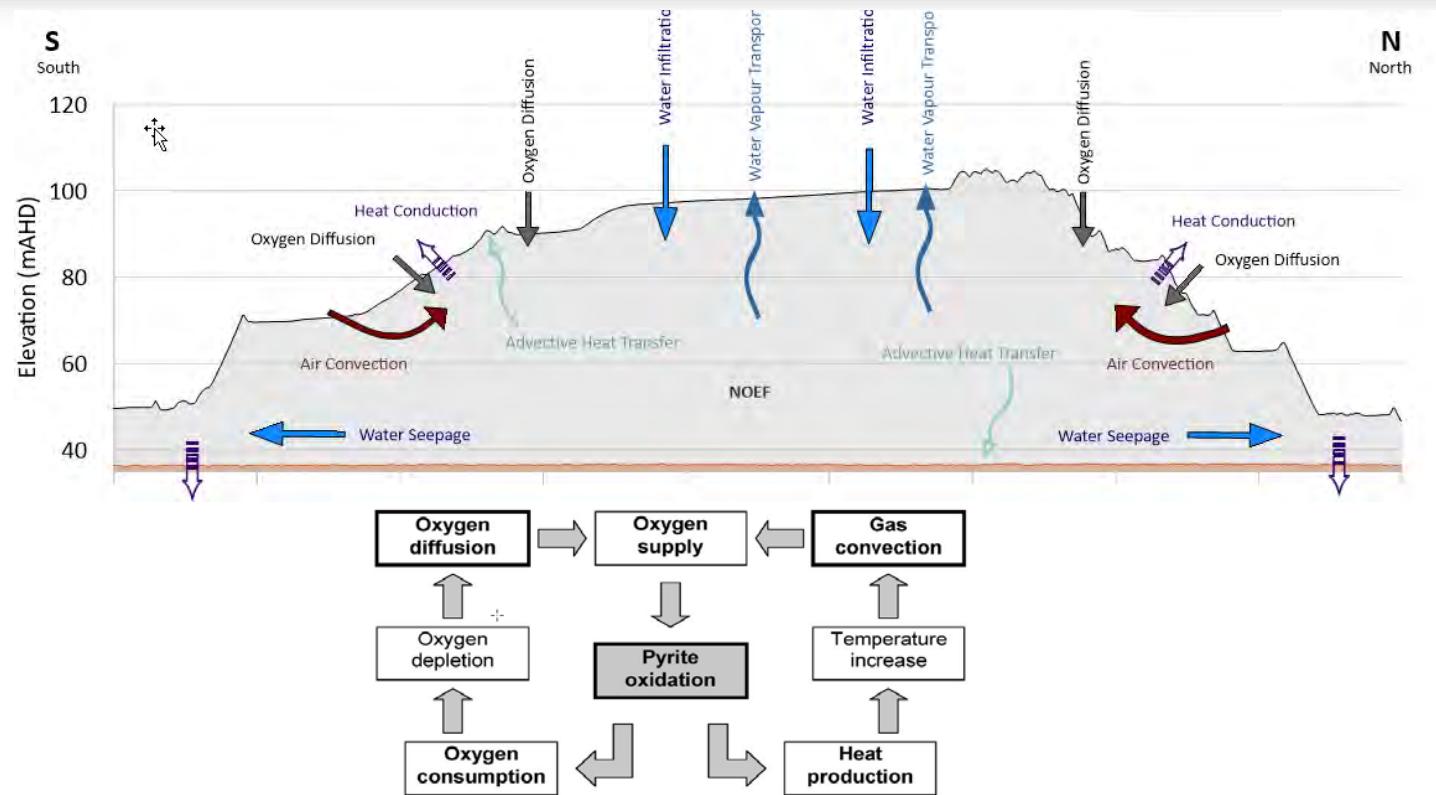
- Far coarser
- Wider range of particle sizes
- Leads to preferential flow under saturated and unsaturated conditions
- Small proportion of waste can contribute to flow and quality changes



# Conceptual cartoon (from GARD \*)



# Conceptual Model (Water, Gas, Heat)

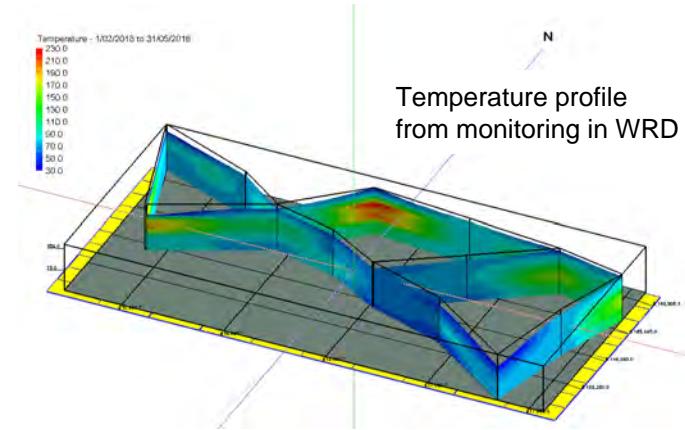
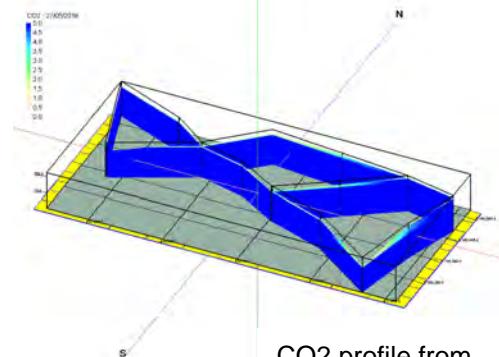




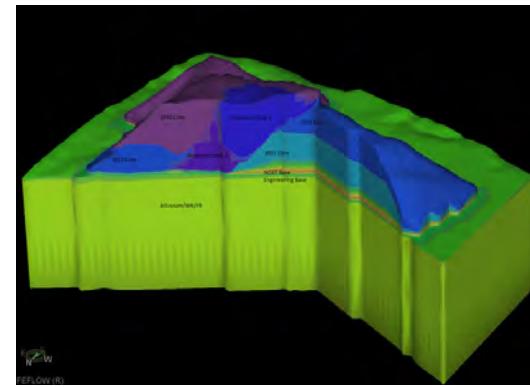
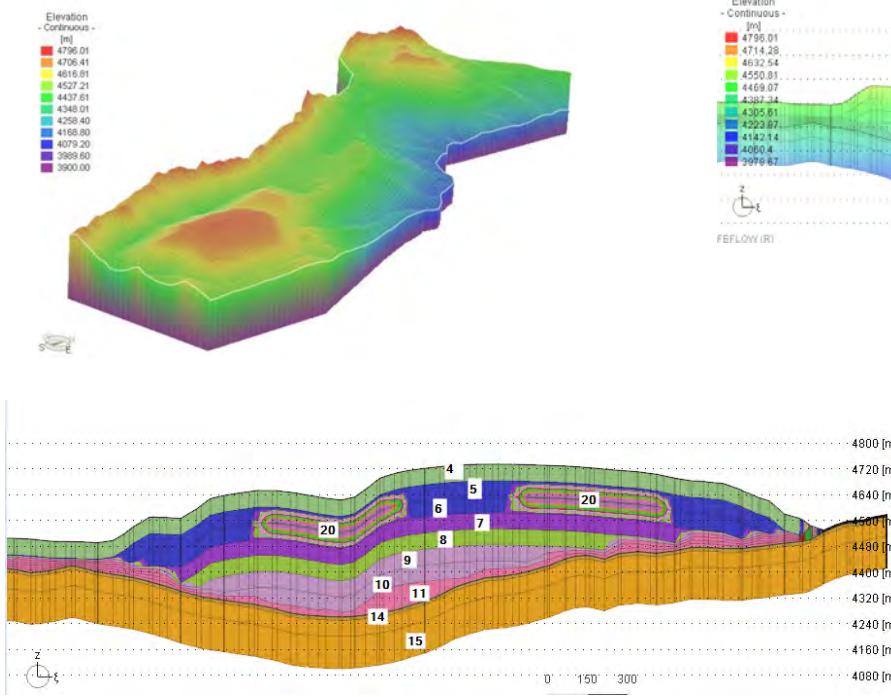
# Understanding processes with monitoring and modeling

Aspects influencing air flow, gas consumption and heat generation

1. Geometrical features
2. Water flow and transfer
3. Geochemical character of rock
4. Heat generation and flow
5. Air flow
6. Oxygen transport

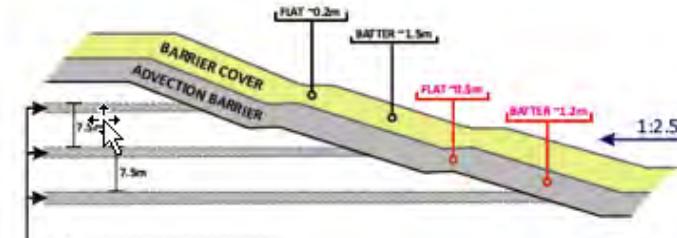
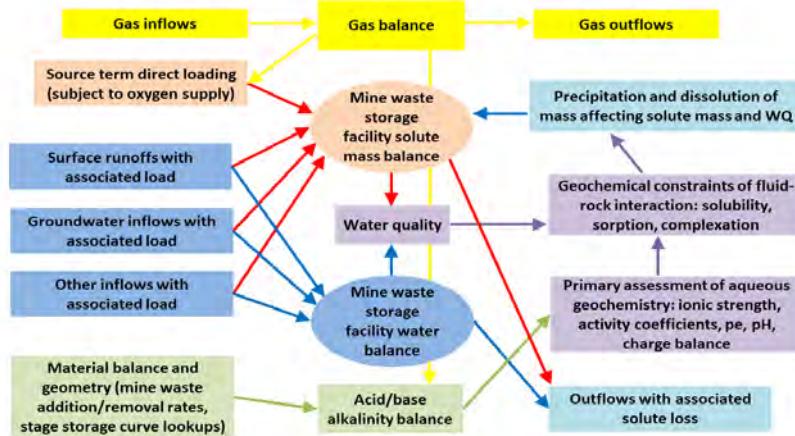


# Modeling heat and gas in 3D using Tough2 and linking to GoldSim or using Geostudio modules



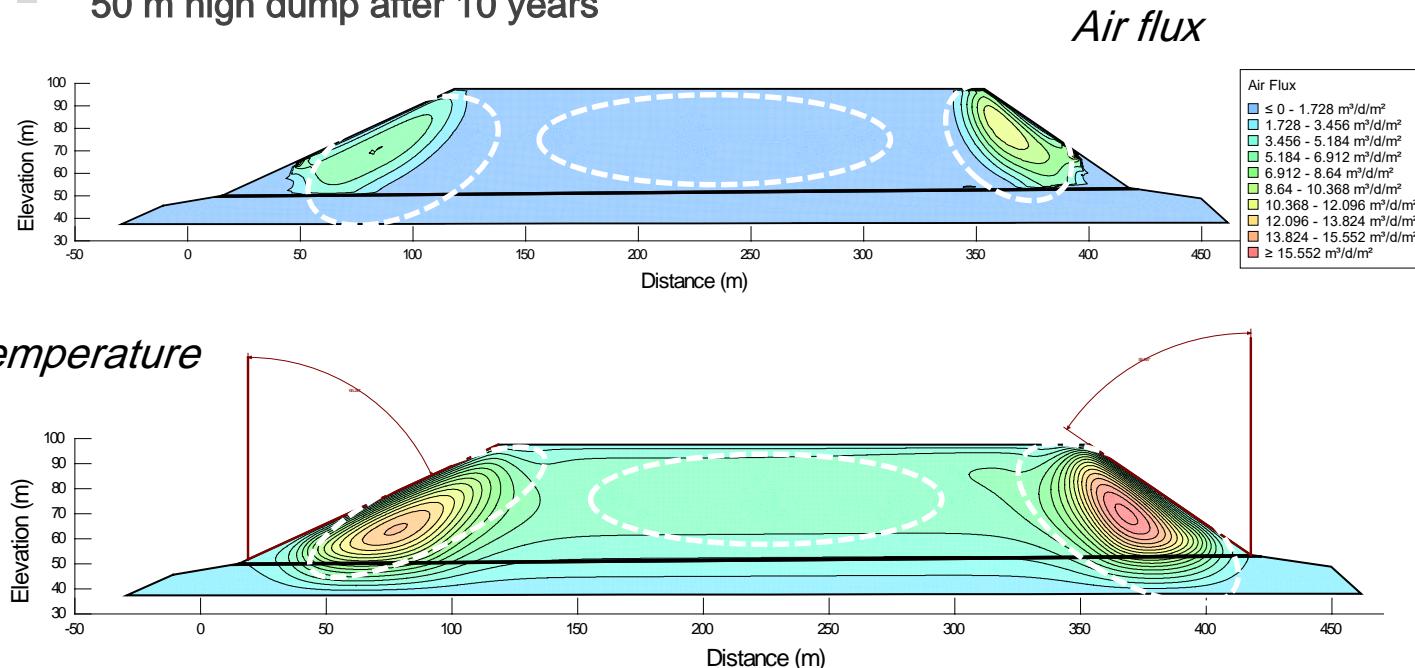
# Modeling Approach

- Dynamic unsaturated/saturated water and gas with heat
  - Tough2 or Geostudio (Seep/W, Air/W, Temp/W)
- Water Quality
  - GoldSim directly uses Tough2 or Geostudio
  - Accounts for low water: rock, temperature and high salinity
  - Also using GWB and ChemPlugIn



# Model results and implications

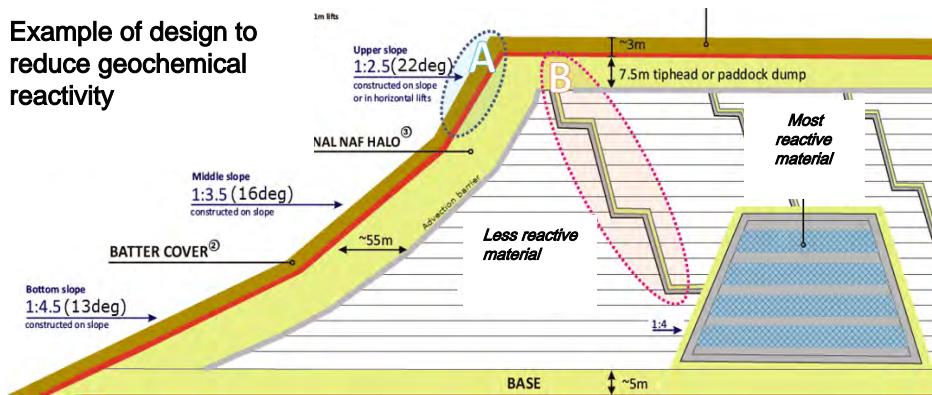
- 50 m high dump after 10 years



# WRD design options

- Placement of most reactive materials as “deep” into facility as possible
- Placement of most reactive materials using methods like paddock dumping rather than long end tips (or have much lower end tip heights)
- Include both interim/progressive covers and final covers (targeting oxygen and water)

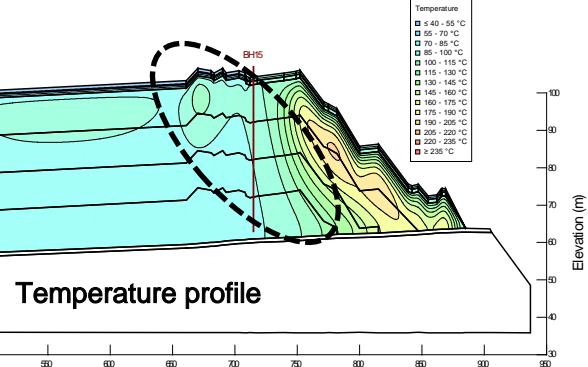
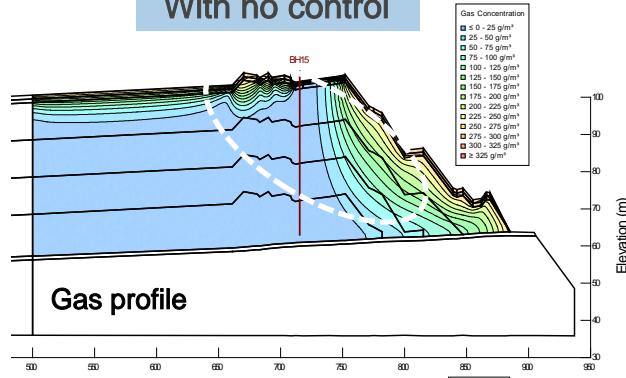
Example of design to reduce geochemical reactivity



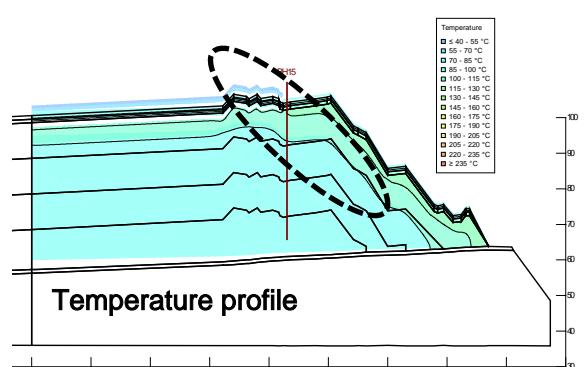
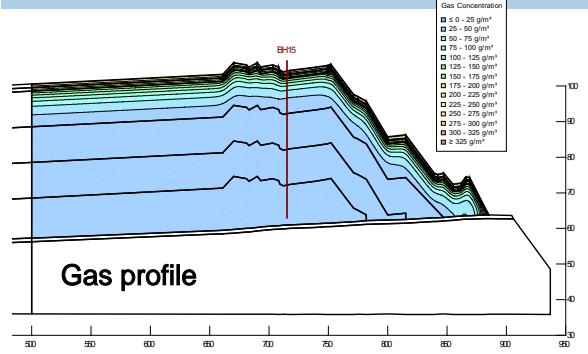
# Heat and Gas Flow Model



With no control



Mitigation: Placement and then covers





# Some design implications

- Placement of waste:
  - Reactive waste away from oxygen
  - Reactive waste not under batters
  - Reactive waste encapsulated in NAF materials
- Placement and scheduling
  - Shorter lifts to break gas transport pathways
  - Shorter lifts to disrupts heat convection
- Covers
  - Timing of placement
  - Limit water and gas (oxygen)
  - Gas more important to lower reactivity



# DESIGN CONSIDERATIONS 4

## Mineral Precipitates & Stability

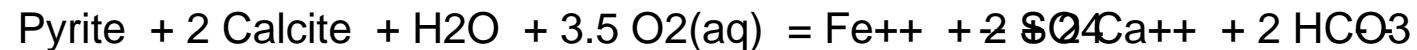
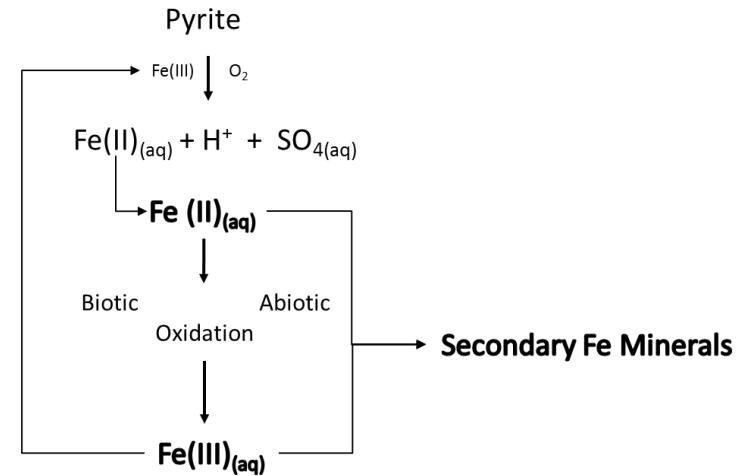
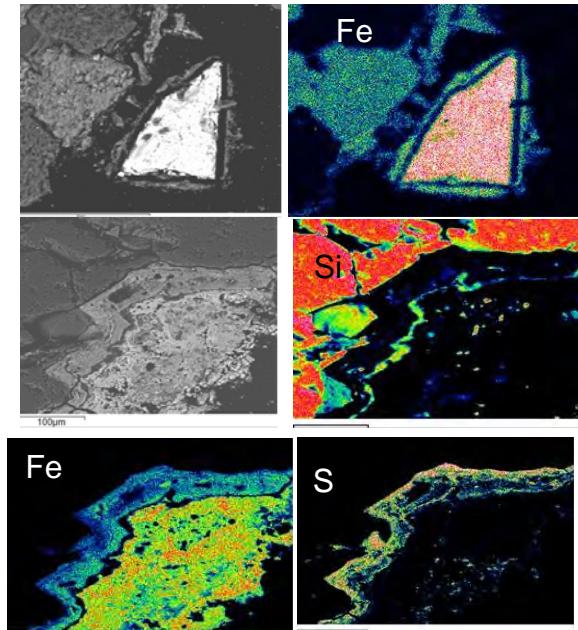


## Basic recipe (#4)

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- Reaction products often form precipitates



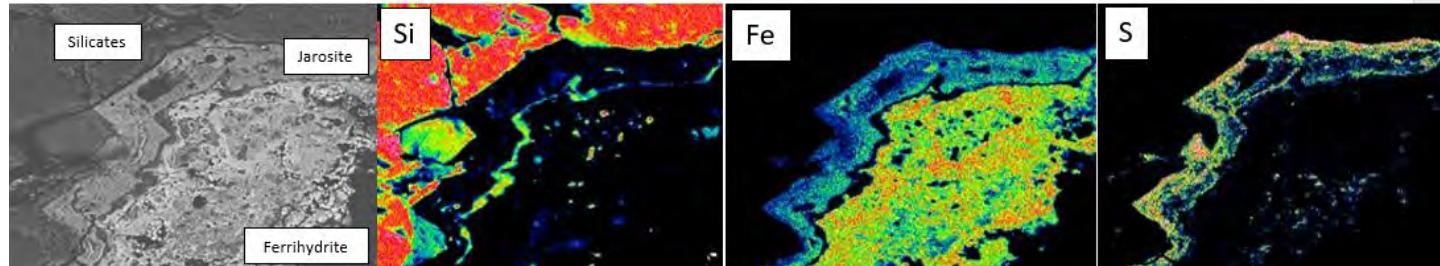
# Geochemical Mechanisms—Sulphide Oxidation and Secondary Minerals\*





# Static tests

- Whole rock analyses
- Shake flask tests
- Leaching tests
- Particle size distribution
- Mineralogy (XRD/XRF)\*
- Detailed analysed (e.g. using electron microscopes\*\*)



# Implications\*



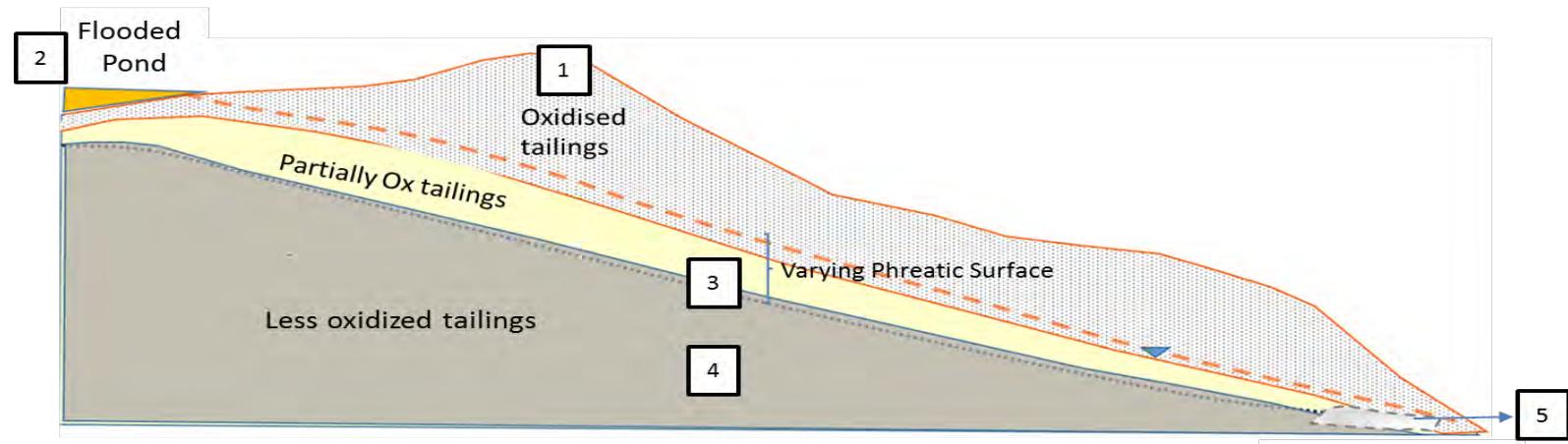
Material does not behave as originally intended



# Implications\*



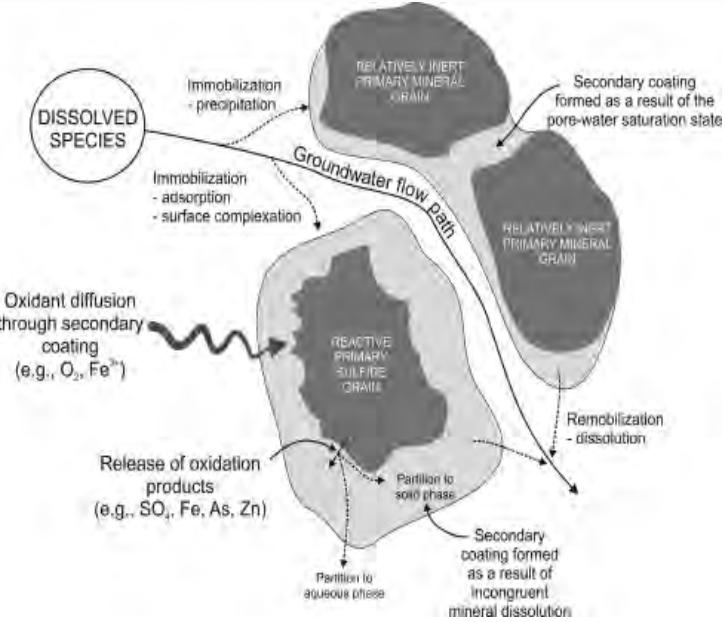
# Clogging drains/altering flow paths\*



1. Tailings Profile
2. Flooded Pond
3. Phreatic Surface
4. Saturated Tailings
5. Dam Toe

*Clogging can block flow paths/ drains: Build up of pore pressure or flows occurring in areas other than the design*

# Implications\*





# Summary from Design Case 4

## So what?

- Physio-chemical changes occur in many TSFs
- Potentially change the long-term risk/stability profile
  - Uncontrolled flows
  - Increased phreatic surfaces
- Regular physical monitoring can identify issues with mineral weathering and precipitate formation but understanding geochemical changes can identify and mitigate issues with existing dams early.
- The importance of evaluating these geochemical systems at the design stage as well as throughout the monitoring stages of ageing facilities will become increasingly important as greater scrutiny is placed on the integrity of tailings facilities.



## Overall summary

- Geochemistry is not blackbox and just “nice to have”
- There are both environmental as well as engineering design reasons to include geochemistry as part of the projects
  - The tools are available
  - Integration with other disciplines (especially design engineers) is where the most benefit to mining projects can be realised
- Integrating geochemistry can save time and money in operations and at closure



# Thank you and acknowledgements

- Thank you for your time and attendance
- Thank you to all of KCB's mining clients to whom we have been able to provide geochemistry services across the world.
- Acknowledgements for assistance with this slide show from our geochemistry teams in Australia and Canada, especially to KCB senior geochemists:
  - Ro Strand, Lindsay Robertson, Terry Harck, Alex Fitzpatrick and Johan Fourie; and,
  - Yuan Tian, Jen DurocherDale Sprague and William Nash



## Q&A

# Questions?

Please enter your questions into the chat box

Additional questions can be sent to [info@klohn.com](mailto:info@klohn.com)