Department of Natural Resources, Mines and Energy

# QUEENSLAND ABANDONED MINES UPDATE

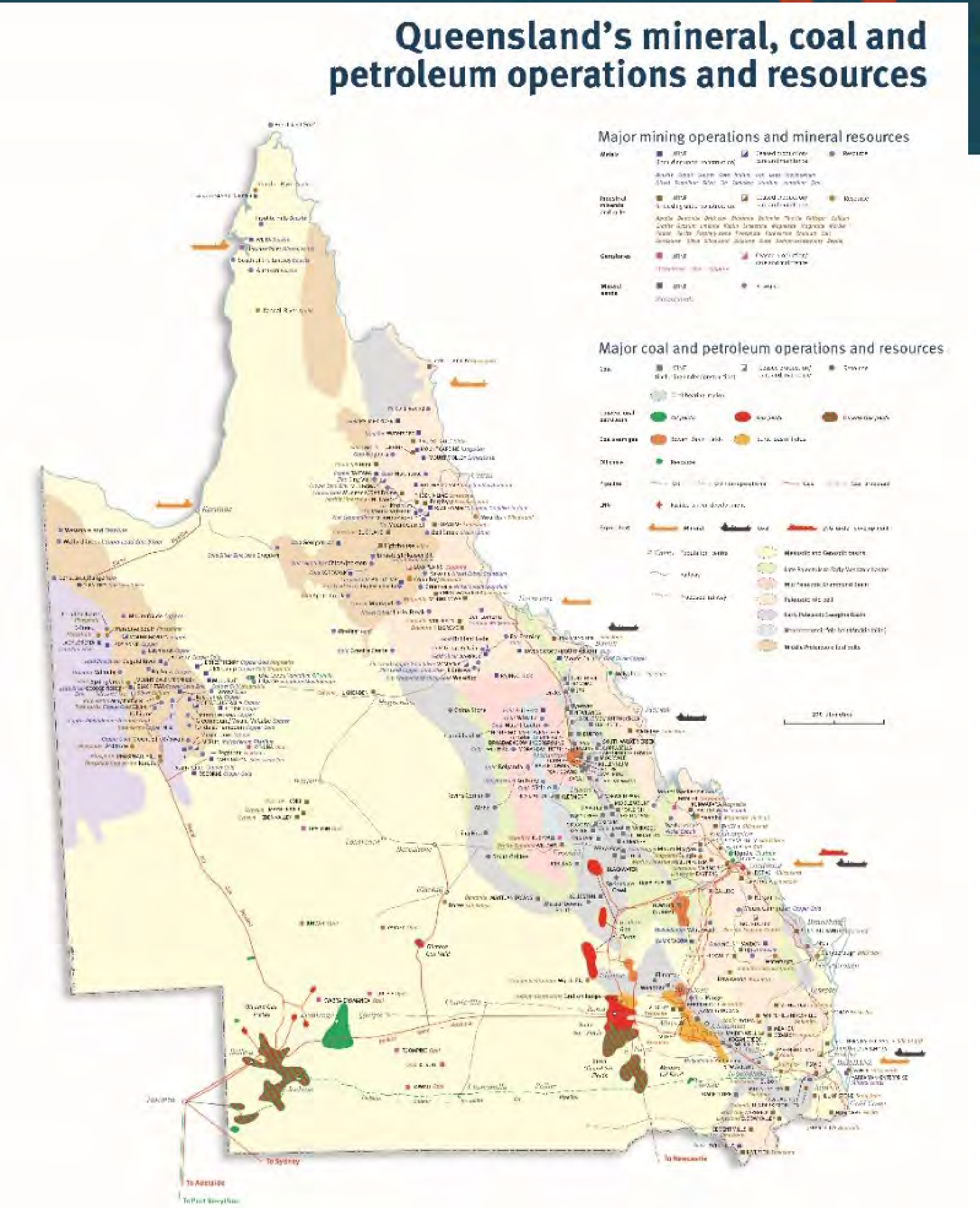
AMD MINI SYMPOSIUM

BRISBANE

02 May 2019

Queensland Government

# QUEENSLAND OVERVIEW




## Resources are distributed across Qld

## Re-classifying Abandoned Mines:

- About 120 sites with modern abandoned mine features
  - Medium to large scale sites,
  - Mechanised mining
  - Sites with potential health, safety, environmental, property risks
  - These are considered the Program sites

# FEATURES OF PRIORITY ABANDONED MINES


Pink sites are Priority, blue sites are Surveillance

# ABANDONED MINES BY DESCRIPTION

Table 1: Characteristics of legacy mines, pre-commencement terminated mines and historical mining disturbances

| | Legacy mines | Pre-commencement terminated mines | Historical mining disturbances |
|---|---|---|---|
| **Description** | Ceased production prior to the Environmental Protection Act amendments in 2000 and have features in common with a contemporary mine created by mechanised mining methods | Ceased production after the Environmental Protection Act amendments in 2001 without fulfilling rehabilitation obligations | Ceased production prior to the Environmental Protection Act amendments in 2000 and do not have features in common with a contemporary mine<br><br>Characterised by small-scale, non-mechanised mining methods |
| **Approximate size** | Medium to very large | Small to very large | Very small to small |
| **Approximate number** | 120 | 4 major sites | 15,000 |
| **Typical commodities** | Precious and base metals, bauxite, tin and coal | All commodities | Precious and base metals, tin, gemstones and coal |
| **Features** | Consistent with surface, underground or alluvial mining methods (e.g. open-cut mines, large underground developments, waste rock dumps, heap leach pads, crushing and processing plants, concentrators, smelters and tailings storage facilities) | Consistent with all mining and resource extraction methods (e.g. open-cut mines, underground developments, waste rock dumps, heap leach pads, crushing and processing plants, concentrators, smelters and tailings storage facilities) | Consistent with surface and underground mining methods (e.g. small waste rock dumps, small shafts with minor underground workings, shallow pits and open or collapsed trenches) |
| **Examples** | • Mount Morgan<br>• Mary Kathleen<br>• Mount Oxide | • Linc Energy Hopeland site<br>• Collingwood Tin Mine<br>• Mount Chalmers Gold Mine<br>• Rishton Gold Mine | • Gympie goldfields<br>• Charters Towers goldfields<br>• Stanthorpe and Herberton tin mining areas |

Extract from Abandoned Mines Discussion Paper

# ALL THE OTHERS…..

Historic mine disturbances (15,000+) features are not included in 120 Program sites

# Recent Initiatives

- Passing of the *Mineral and Energy Resources (Financial Provisioning) Act 2018*

- Discussion Papers released

| Discussion papers closed | Date closed |
|---|---|
| *Financial Assurance Review – Providing Surety* | 22 September 2017 |
| *Financial assurance framework for reform* | 15 June 2017 |
| *Better Mine Rehabilitation for Queensland* | 15 June 2017 |
| *Achieving improved rehabilitation for Queensland: other associated risks and proposed solutions* | 16 July 2018 |
| *Achieving improved rehabilitation for Queensland: addressing the state's abandoned mines legacy* | 16 July 2018 |
| *Managing residual risks in Queensland* | 1 February 2019 |

# Looking Forward

- Establishment of the Financial Provisioning Scheme
  - Middle of 2019
  - 3-year changeover / implementation
  - Immediate support for newly abandoned sites that have contributed to the Scheme
  - Or where Financial Assurance exists
  - Future Funding for Legacy Abandoned Mines from the Fund Interest
  - Support for research and innovation
- Smaller legislative changes to support activities on abandoned mines
- Collaboration to support innovation for re-commercialisation and repurposing

# Challenges

**Need innovation to support:**

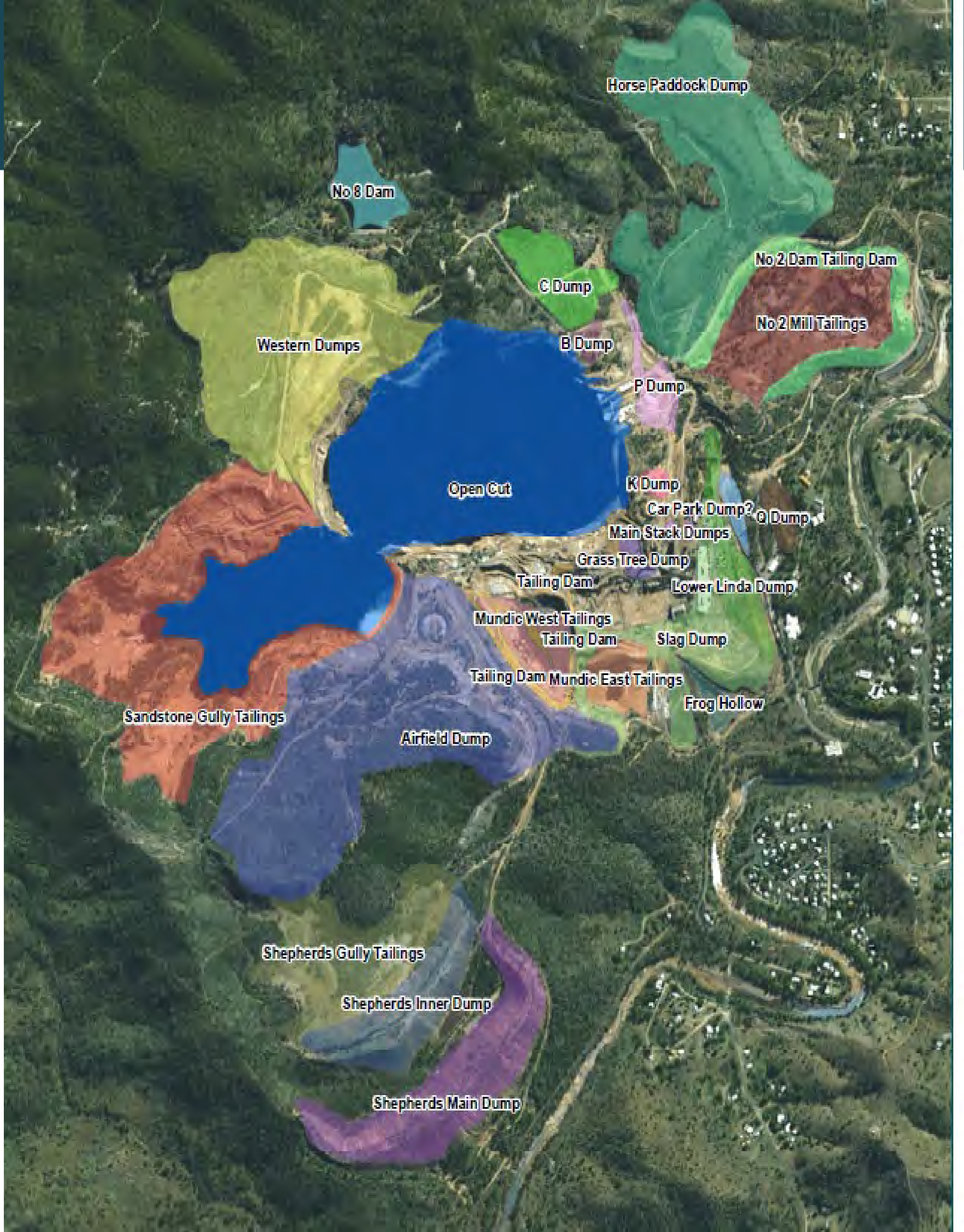
- Effective mine closure strategies
  - Planning for successful closure
  - Delivering rehabilitation outcomes
  - Residual Risk Management
- Methods to deal with mining legacies and poor decisions in the past
  - Acid mine drainage
  - Stockpile placement
  - Legacy site risks and impacts
- Efficient ways to re-assess residual resources
  - Sampling of stockpiles
  - Understanding the geological and mineralogical contexts
  - Assessment of mineral extraction options
- Economic mineral recovery methods
  - Improved efficiency of existing technologies
  - New technologies
- New productive uses for sites after mining
  - Mindful of community concerns and expectations
  - Effective consultation

# AMD Case Studies

- Major sites with AMD issues:
  - Mount Morgan
  - Mount Oxide
  - Mount Chalmers
  - Croydon Federation Mines
  - Horn Island Gold Mine

# Mount Morgan

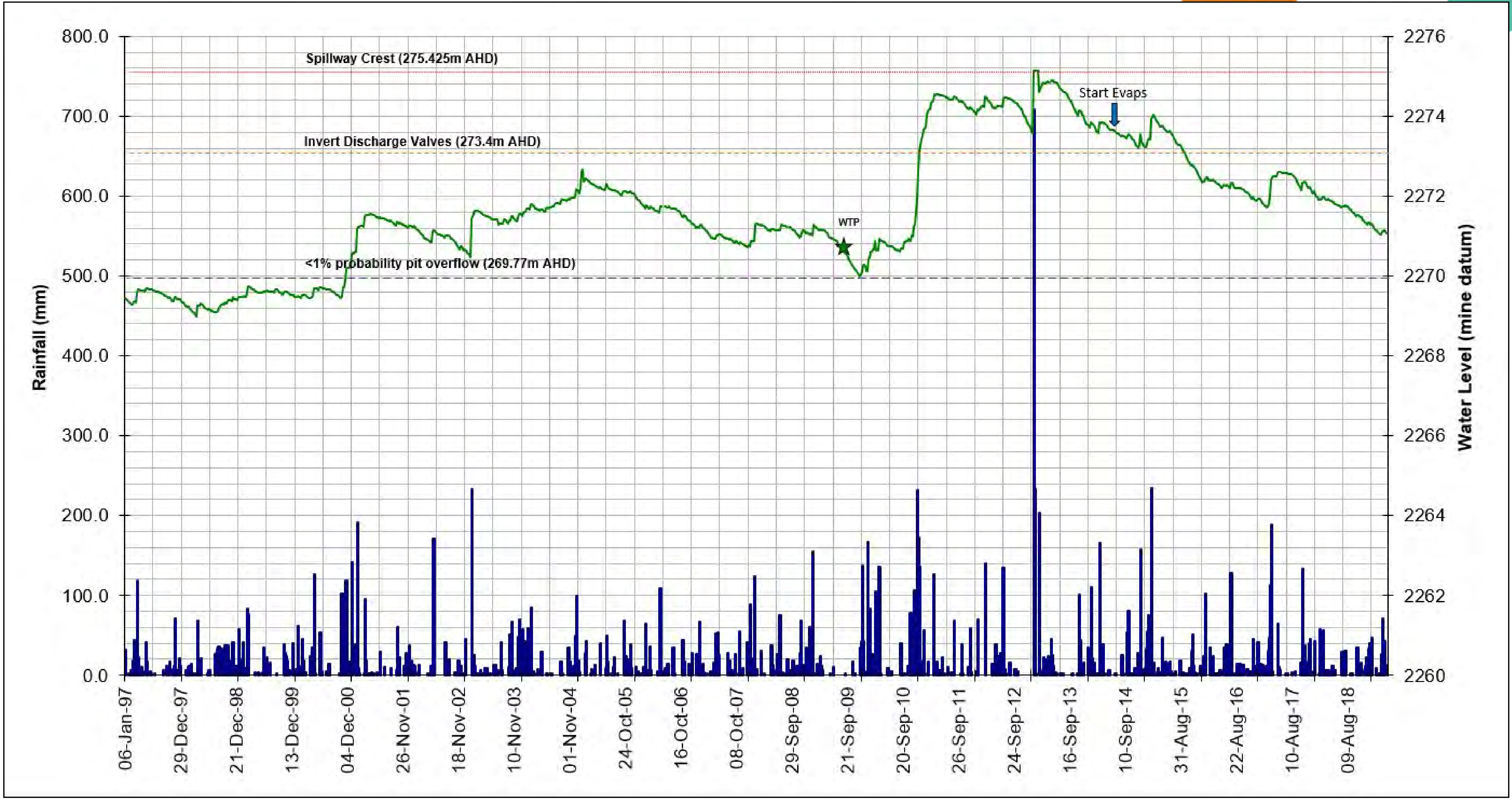
- Mined from 1882 to 1990
- Mine Pit contains about 10.5 GL of water
- pH3.5, EC17000, high sulphates,
- elevated concentrations Al, Cu, Cd, Zn
- 900ML seepage collected annually from 9 sites, pumped back to mine pit
- Lime Dosing WTP
  - Up to 2.3ML/day treated water discharged
  - Low density sludge returned to the Mine Pit
  - Slaking water challenges
- 3 Evaporators remove up to 1ML / day from Mine Pit



# Site Challenges

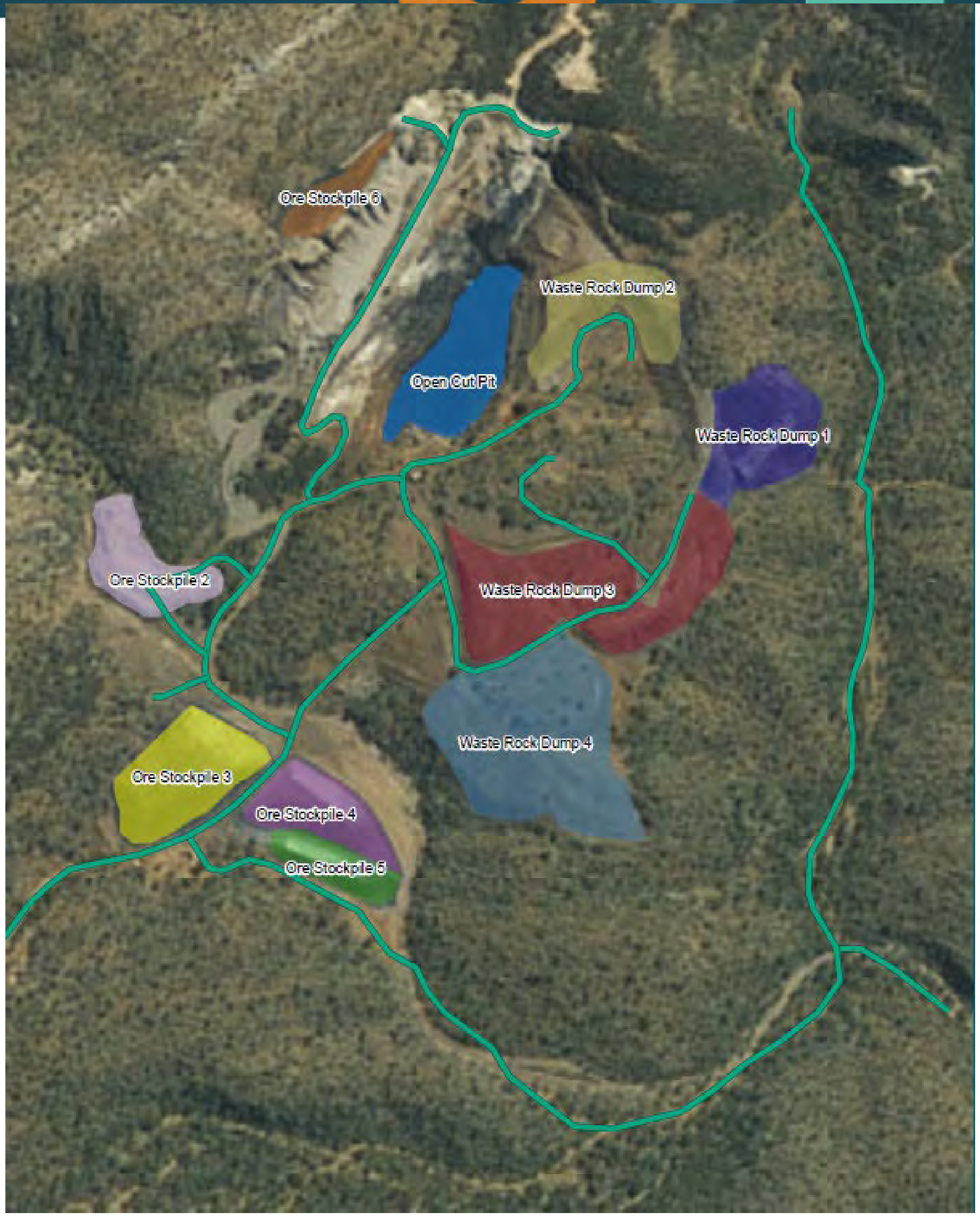
- Water management
  - Mine Pit water balance
  - Raw water supply for WTP
  - Runoff Management
  - ARD impact minimisation
- Offsite impacts
- Site heritage management
- Tailings Reprocessing as an economic driver for site remediation

# Mine Pit Water Level & Rainfall History



# Mount Oxide

- Mine Pit Water Volume: ~140ML
- Pit Water Quality: pH 2.3-2.8 (seasonal variation)
- Streams turn blue after large rainfall events



# Mount Oxide

- Site Management Challenges:
    - Remote site – nearest populated town 200km away
    - No mains power, limited capping materials, poor road infrastructure
    - High-intensity rainfall events
    - Stream Impacts after large rainfall events
    - Exploration Permit over the site
    - Heritage (e.g. Ernest Henry's Cave)
    - Landholder concerns
    - Public and media attention

# Mount Oxide

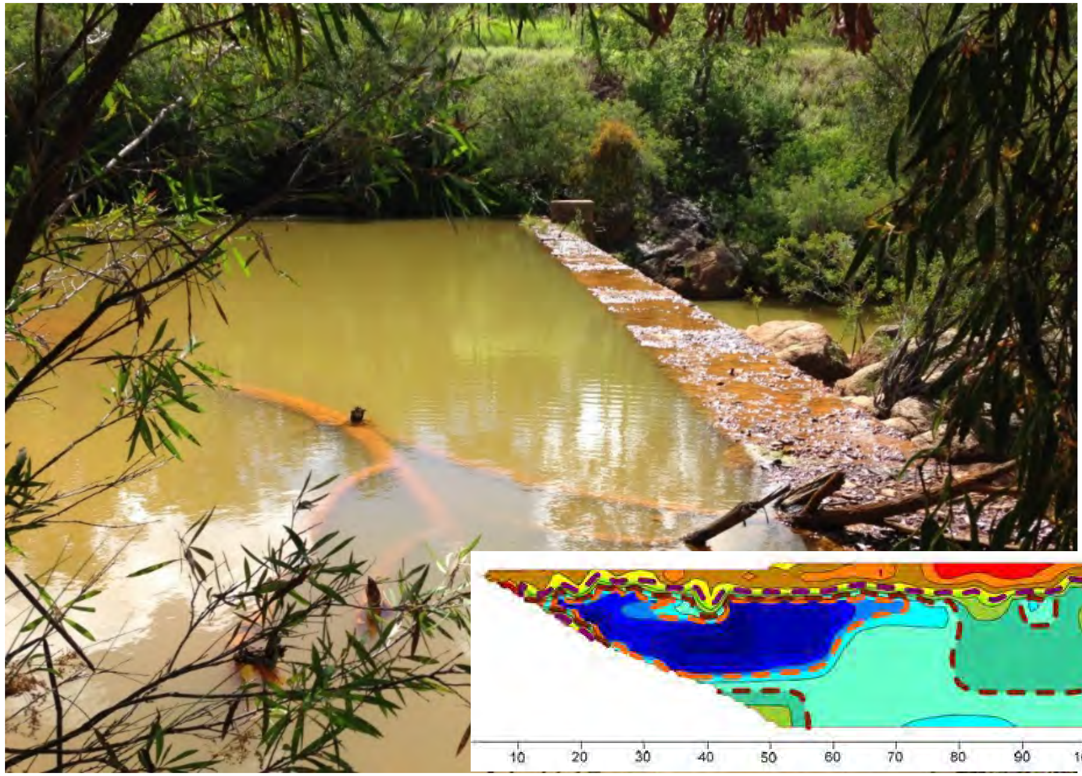
- Management / Mitigation
  - Poly lining over AMD generating material
  - Post rainfall runoff catchment and pump back to mine pit
  - Clean water diversions

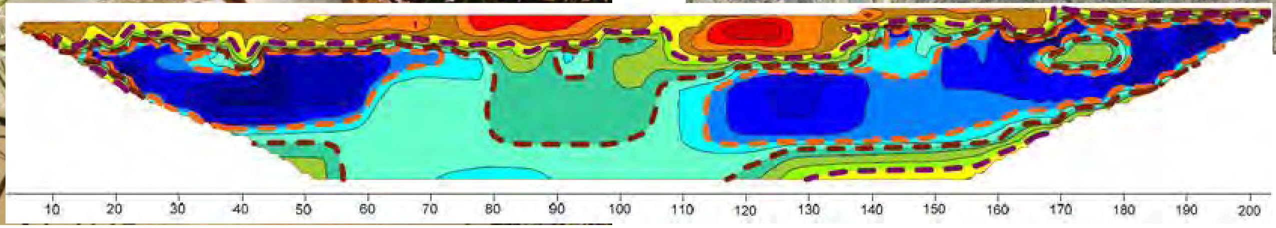
# Mount Chalmers

- Site Overview:
  - 12 ha of contaminated catchment
  - Mine Pit capacity 710 ML
  - Seepage from stockpiles and tailings dam
  - Discharges from the Mine Pit after heavy rainfall
- Risk Mitigation Strategy:
  - Seepage return system
  - Clean water diversions - have achieved negative water balance for mine pit
- Site Challenges:
  - Remaining resource and Exploration Permit
  - Funding for remediation

# Herberton Tailings Dam

- Dams were capped in 1997 to address community dust concerns
- Ongoing seepage issues with downstream impacts



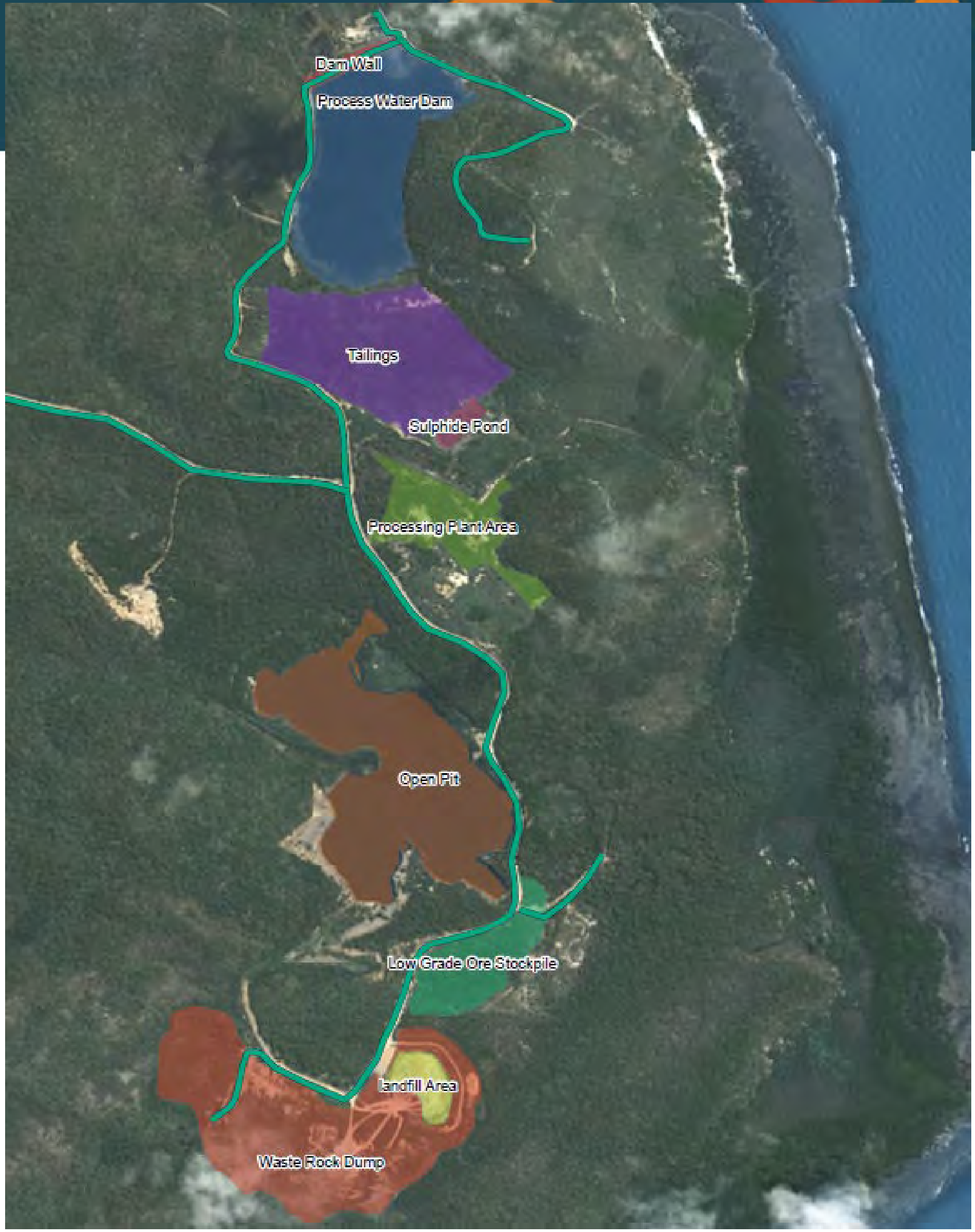
# Croydon Federation Mines

- Multiple mines
- Large partially capped Waste Rock Dump
- Telemetry and seepage pumpback
- Runoff Management

# Croydon Seepage


# Horn Island Gold Mine

- Mine operated from 1989-1991
- AMD from Tailings Dam, Large WRD
- Also Process Water Dam wall,
  - Constructed of sulphide bearing waste rock
- Reef at fringe of island



# Thank you!

Questions?

# WHAT DO WE WANT TO HAPPEN?

- Minimise issues with mines failing in the future
  - Good mine planning
  - Stronger progressive rehabilitation requirements
  - Financial Provisioning
- Refined processes to manage failures
  - Response to disclaiming and other circumstances
  - Effectively deal with risks – safety, health, environmental, business, community
- Assess Residual Resources and Re-Commercialisation Opportunities
  - Tailings and unmined portions of orebodies
  - Stockpiles
  - Presence of new minerals in demand - reassessments
- Find drivers to remediate sites
  - From resources, existing infrastructure opportunities
  - Other uses?

# SITE MANAGEMENT STRATEGY

- Sites managed by DNRME after abandonment or Disclaim
- Reconfigured Abandoned Mines Program Structure
  - Planning and Assessment
  - Operational Management of legacy sites
  - Major Projects
  - Reporting and Engagement
  - Policy and Technical and Innovation
- Scalable response dependent on need and funding available
- Forward Works Program prioritised on Risk

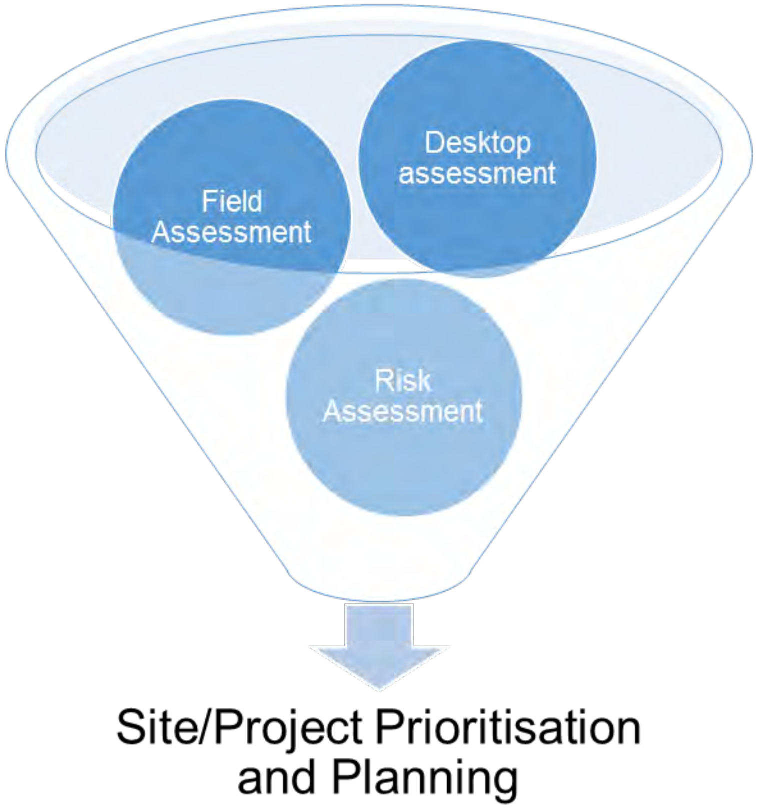
# SITE MANAGEMENT STRATEGY

- Sites managed by DNRME after abandonment or Disclaim
  - Site Inspection and Risk Assessment
  - Initially make safe and secure
  - Develop durable site management strategies
  - Review residual resources and other potential productive uses
  - Strategy for Re-commercialisation or Remediation based on the above

# Planning and Assessment

## Site Prioritisation Strategy

1. Review and develop program sites (priority and surveillance sites)
2. Preliminary desktop risk assessment for sites
3. Prioritisation of sites for field assessment
4. Detailed site risk assessments into risk management system
5. Prioritisation of projects based on priority sites and risks
6. Review all sites for re-commercialisation and re-use options
7. Two and five year planning based on risks



# DATA SYSTEMS IMPROVEMENT

**Field Tool And Geodatabase:**

- New Field tool rolled out for site and features mapping
- Past data has been migrated into geodatabase
- Current focus is populating Geodatabase with program site features

**Mine Information Management system:**

- Implementation of a new Mine Information Management System (MIMs) for future (abandoned) mines as part of the new FA framework
- MIMs will be a database for all mine related information for mines operating and abandoned under the FPS

**ESdat**:

- Scoping use as a state wide analytical database

**Risk Management System:**

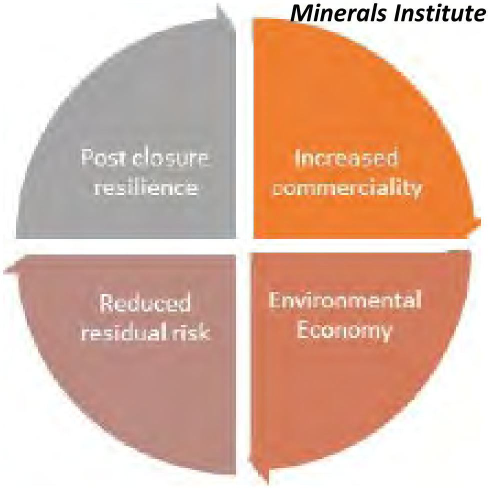
- Incorporation of abandoned mines risks into departmental risk management system
    - Inclusion of a risk model for prioritisation of abandoned mine program sites

# Repurposing and Reprocessing

## Innovation Opportunities and Support

- Mount Morgan
  - Reprocessing Strategy
    - Met with Norton executive management Feb 28
  - Tourism – Fireclay Caverns
- Innovation - Universities
  - SMI Research Fellowship –
    - Jumna and Rishton tailings,
    - Wolfram Camp tailings review
  - DG letter of support for SMI Strategy – Transforming the Mine Lifecycle
  - Possible CRC for Resource Sector Environmental Management / Mine Rehabilitation
  - Innovation ecosystems
    - Tie in with Centre for Social Responsibility in Mining, Business Schools at UQ and QUT
    - Residual Risk parallel work
- Innovation Challenge – Mining Equipment Technology Services groups (METS)
  - Tailings reprocessing and waste water treatment
    - Working with DSDMIP and METS Ignited Cluster Groups
  - JKMRC potential collaboration – mineral resource characterisation, extraction feasibility


***Diagrams by Sustainable Minerals Institute***



# Financial Assurance and Mining Rehabilitation Reforms

Maria Rosier – Department of Environment and Science
Peter Fox – Queensland Treasury

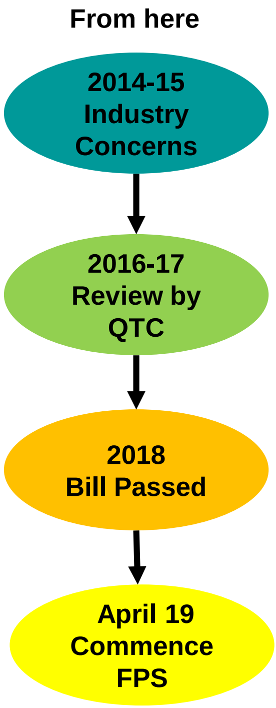
# Agenda

1. Background
2. Mineral and Energy Resources (Financial Provisioning) Act 2018
   - Financial Provisioning Scheme
   - Rehabilitation Reforms
3. Implementation
4. Other Government Reforms
5. Questions

# Background

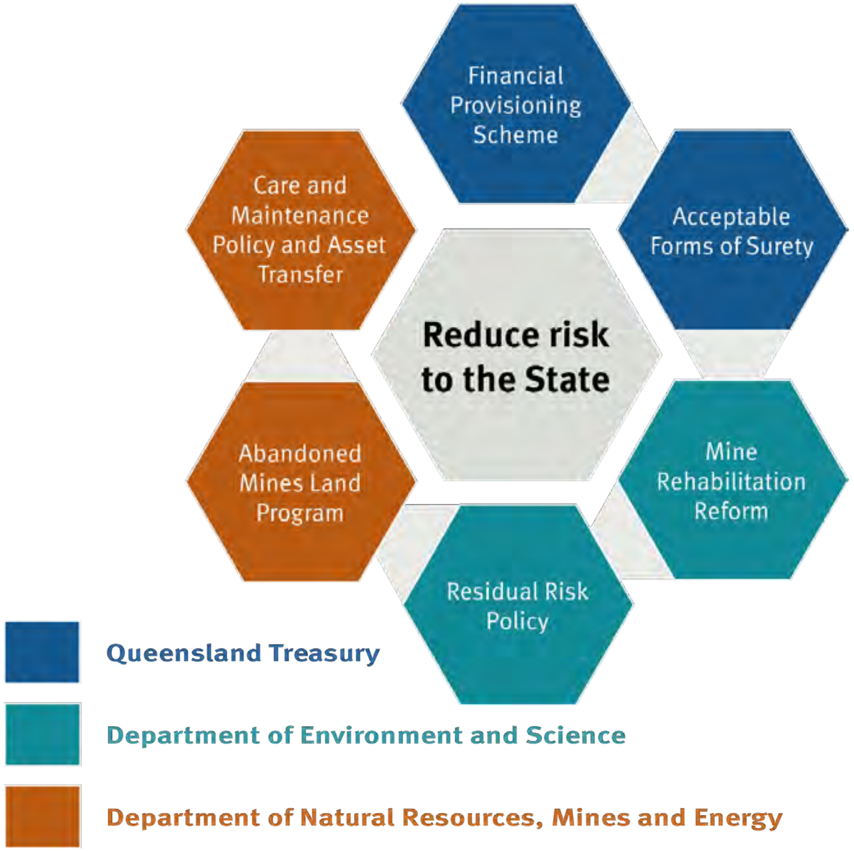
- **2014-2015 – Emerging Issues**
  - Industry identified that the Financial Assurance framework was costly and a barrier to investment in the resources sector
  - Industry sought more clarity on the Government’s Policy and expectations for rehabilitation of mine sites
  - Government incurred financial costs when a number of mine sites did not fulfil their environmental obligations

- **2016-2017 - Queensland Treasury Corporation Review**
  - Increased exposure to rehabilitation liability (e.g. due to discounts, lack of clarity on rehabilitation requirements, flawed process for tenure transfer etc)
  - Need for clarity of roles and responsibility
  - Streamline of data collection
  - No source of abandoned mines funding



# Financial Assurance Reforms

- Whole of Government approach
- Project Management Office
- Continuous stakeholder engagement



# Mineral and Energy Resources (Financial Provisioning) Act 2018



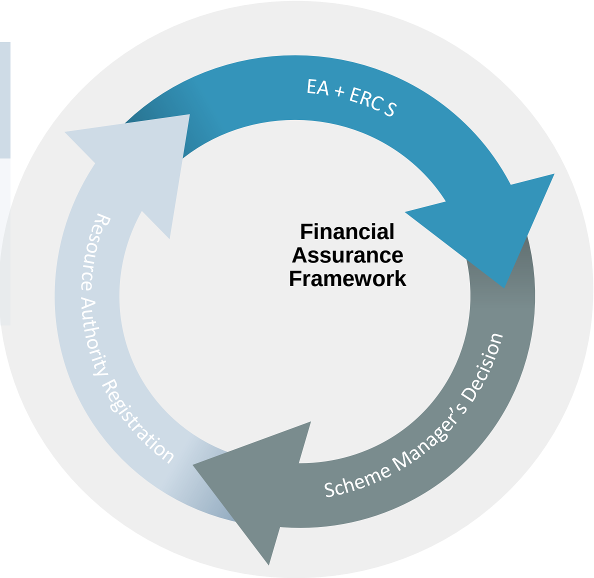
The Mineral and Energy Resources (Financial Provisioning) Act 2018 and its supporting policies, helps realise 3 of the 6 reforms:

1. Financial Provisioning Scheme - FPS (for all resource activities)
2. Progressive Rehabilitation and Closure Plans - PRCP (for mining)
3. Acceptable Forms of Surety

# Improving Financial Assurance Outcomes in Qld

## Resource Authority Registration

DNRME will only register the resource authority on MMOL following notification that the FA has been paid to the Financial Provisioning Scheme




## Environmental Authority + Estimated Rehabilitation Cost

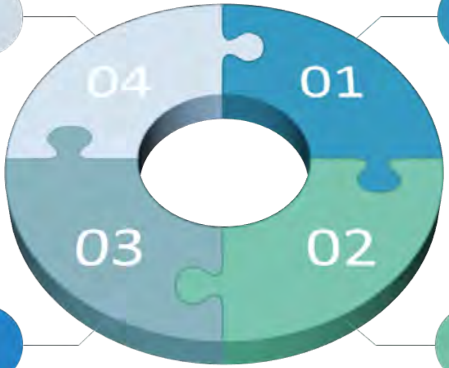
Environmental Authority Application Process
Estimated Rehabilitation Cost (developed using a calculator)
ERC = initial risk allocation (as a transitional arrangement)

## Scheme Manager's Decision

Initial Risk Allocation if > $100K ERC
Requirement to pay surety or pool contribution
Following FA payment – notification to DNRME

# Financial Provisioning Scheme

## How does it work?




### Surety
- Bank Guarantees
- Insurance Bonds
- Cash

### Scheme Manager
- Statutory Officer
- Liaise with DES & DNRME
- Decision Maker

### Scheme Fund
- Annual Contributions
- Pooling of Risk
- Site Rehabilitation, Abandoned Mines, Research & Development

### Risk Assessment Process
- Risk Allocation Process
- Annual Review

Commenced 1 April 2019

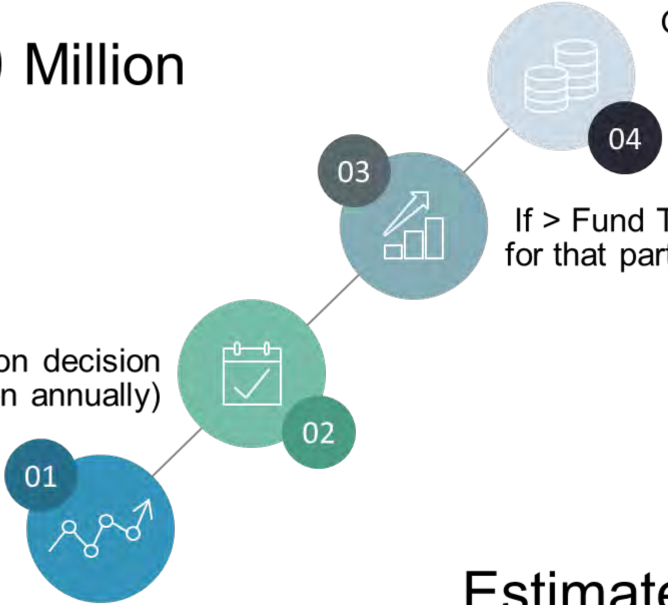
# Risk Assessment Process

- **Risk Allocation**
  - Resource Project Strength
    - Remaining Economic Life
    - Off-Take Arrangements
  - Rehabilitation
    - Extent of Certified Rehabilitation Completed under EA
    - Progress towards PRCP
  - Compliance Record
    - Relevant compliance issues relating to the EA
    - Relevant compliance issues relating to the resource tenure
  - Financial Soundness
    - 3 years of audited financial statements
    - Credit rating (approved by Qld Treasury or not more than 12 months old).

# Requiring Surety to preserve the FPS Fund

## Fund threshold $450 Million

## Estimated Rehabilitation Cost (ERC) >$100,000




Total ERC = the sum of the ERC for each EA

Scheme Manager make allocation decision (initial, then annually)

If > Fund Threshold, then surety is required for that particular EA.

Surety may be in the form of a Bank Guarantee, Insurance Bond or Cash

# Mine Rehabilitation Reform

## Objective:

- Enhance planning to achieve progressive rehabilitation
- Clarity for business on standards for rehabilitation and relinquishment
- Certainty for government, community and business on rehabilitation outcomes

- Reform will commence by a date set by regulation that is no later than 1 November 2019

**Mine Rehabilitation Reform**

# Mine Rehabilitation Reform

- The MERFP Act and supporting legislation and guidelines implement the Queensland Government's Mined Land Rehabilitation Policy.
- The Government is committed to ensuring land disturbed by mining activities is rehabilitated to a safe and stable landform that does not cause environmental harm, and can sustain an approved post-mining land use.

## Mined Land Rehabilitation Policy

**The Queensland Government is committed to ensuring land disturbed by mining activities is rehabilitated to a safe and stable landform that does not cause environmental harm and is able to sustain an approved post-mining land use.**

Land disturbed by mining activities will be rehabilitated progressively as it becomes available, to minimise the risks of environmental impacts and reduce cumulative areas of disturbed land.

The progress and outcomes of progressive rehabilitation activities will be monitored and reported on to demonstrate how successful they have been in achieving progress towards the approved post-mining landform, and to inform corrective action where required.

To provide certainty about the outcomes and timing of rehabilitation, all site-specific mines will prepare a Progressive Rehabilitation and Closure Plan (PRCP). The plan will include binding, time-based milestones for actions that achieve progressive rehabilitation and will ultimately support the transition to the mine site's future use.

Disturbed land associated with mining activities is considered available for rehabilitation unless it is:

- being actively mined, or
- being used for operating mining infrastructure, or
- overlaying a probable or proven resource reserve identified for extraction in the approved PRCP within 10 years, or
- the site of built infrastructure that will be retained as a beneficial asset in the approved PRCP.

Land disturbed by mining activities is considered to be rehabilitated when it can be demonstrated it is safe, stable, does not cause environmental harm, and is able to sustain the post-mining land use approved in the PRCP.

Department of Environment and Heritage Protection
Department of Natural Resources and Mines
Queensland Treasury

# Progressive Rehabilitation and Closure Plans

| Planning Part | PRCP Schedule |
| --- | --- |
| • Project description<br>• Mine plan<br>• Final site design<br>• Rehabilitation methodologies<br>• Consultation with stakeholders | • Maps with final site design<br>• Tables of time-based milestones<br>• Clear completion criteria |

# Key concepts

- Post mining land uses
- Non-use management areas
  - Public interest evaluations
- Milestones and milestone criteria

- The Department is developing regulations, statutory guidelines and other materials to support implementation.

# Laws are not retrospective

**Existing EA's**

- 3 Year Transition Period
- No Immediate Action Required
- Existing rights are preserved

**New EA's**

- Site-specific EA application + Proposed PRC Plan
- Need to comply with the full requirements

# Post approval dealings



Amendments (major and minor)

Amalgamations

Transfers

# Other Government reforms (2019/2020)

- *Managing Residual Risks in Queensland Discussion Paper*
- Care and Maintenance Policy and Change of Control/Asset Transfer
- Abandoned Mines Land Program

# Other Government Reforms (2019/2020)

**Objective:**

- Mitigate environmental and safety risks associated with higher risk abandoned mines
- Create opportunity to commercialise remaining resources in abandoned mines
- Incentivise private investment in abandoned mines

Abandoned Mines Land Program

**Status:**

- Consultation ended in July 2018
- Further consultation and proposals in 2019
- Department of Natural Resources, Mines and Energy

# Other Government reforms (2019/2020)

**Objective:**

- Improve the State's ability to manage resource sites that enter care and maintenance
- Assess the financial and technical capabilities of resource authority holders when a transfer occurs
- Manage resource authorities disclaimed by liquidators

Care and Maintenance Policy and Asset Transfer

**Status:**

- Public consultation ended in July 2018
- Further consultation and proposals in 2019
- Department of Natural Resources, Mines and Energy

# Other Government reforms (2019/2020)

**Objective:**

- Certainty for business on residual risk assessment and calculation methodologies
- Clarity for post surrender management of land
- Transparency in management of residual risk funds

**Status:**

- Managing Residual Risks in Queensland Discussion Paper

Department of Environment and Science

Residual Risk Policy

# Questions?

**Department of Environment and Science Website:**

**DES Mining Reforms - https://environment.des.qld.gov.au/management/env-policy-legislation/mining-rehabilitation-reforms.html**

**FAQ's - https://environment.des.qld.gov.au/management/env-policy-legislation/mining-rehab-reforms-faqs/**

**Queensland Treasury Website:**

**Financial Provisioning Scheme - https://www.treasury.qld.gov.au/resource/financial-provisioning-scheme/#heading--2**

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

BRISBANE convention & exhibition CENTRE

Brisbane, Australia's invitation to host the

# 12th INTERNATIONAL CONFERENCE ON ACID ROCK DRAINAGE

# Why Australia?

1. Experience and networks
2. A delegate-friendly destination
3. People-centred approach


# EXPERIENCE

- Global INAP partner
- Active local network
- Successful AMD Workshop series

# A wealth of experience

- Applied experience in all aspects of mine water management
- World-leading research, which has led to a number of globally applied tests and guidelines
- Evolving stakeholder governance and policy frameworks, focus on mine closure and legacies

# Established AMD network

- Integrated network across industry, government and academic institutions
- Successful history of applied research and innovation
- Well-supported AMD Workshops held at regional locations around Australia

# Strong local support

# BRISBANE

- Sub-tropical climate
- Safe, compact, walkable city
- World-class infrastructure
- Friendly, welcoming city
- Demonstrated success with major events

# Global and local connections

- Direct flights to 31 international destinations
- Second runway to be open in early 2020, doubling flight capacity
- Brisbane Airport to CBD in 20 mins & discounted Airtrain tickets
- Free city transport options for delegates

# A world-class venue in the BCEC

- AIPC World's Best Convention Centre 2016-2018
- Boutique and flexible meeting spaces
- Free wifi and Conference App
- Integrated Registration Desk & Convenors Office
- Award-winning food!

# Integrated program

- Proposed week Aug 30$^{th}$ to Sep 3$^{rd}$ 2021
- Three and a half day technical program covering range of key themes
- Short courses e.g.
  - ARD Fundamentals
  - GARD Guide
  - Cover Design
- Field trips
  - Pre and post event
  - 1 to 3 day duration
  - Multiple options

# Partner program – reef to rainforest

Iconic Australian experiences all within one hour of Brisbane

- Lone Pine Koala Sanctuary
- Tangalooma Resort day trip
- Beach and rainforest day trip
- Mirrabooka Indigenous Experience
- Australia Zoo
- Great Barrier Reef

# PEOPLE

- Stakeholder engagement
- Young professionals
- Committed team

# Stakeholder and future leaders

- A key theme for the conference will be stakeholder engagement

- Also a focus on Future Leaders through special sessions, student scholarships, and other engagements


HOPE TO SEE YOU
IN BRISBANE FOR
ICARD 2021

9th Australian Acid and M ×

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# Committed UQ and BCEC team

Kylie

Mansour

Abbie

Robin

# Video

Rio Tinto

# Strategies for Managing Chemically Reactive Mineral Waste

Rosalind Green, Steven Lee, Lisa Terrusi, Chris Kleiber, Kate Glasson

# Overview of Strategic Principles

1. Sound science

2. Evaluation and prioritisation of risks

3. Transparency, collaboration and an ability to work and share learnings

4. Management practices that are supported by a business case

5. Long-term environmentally protective management practices

6. Strive to improve environmental performance

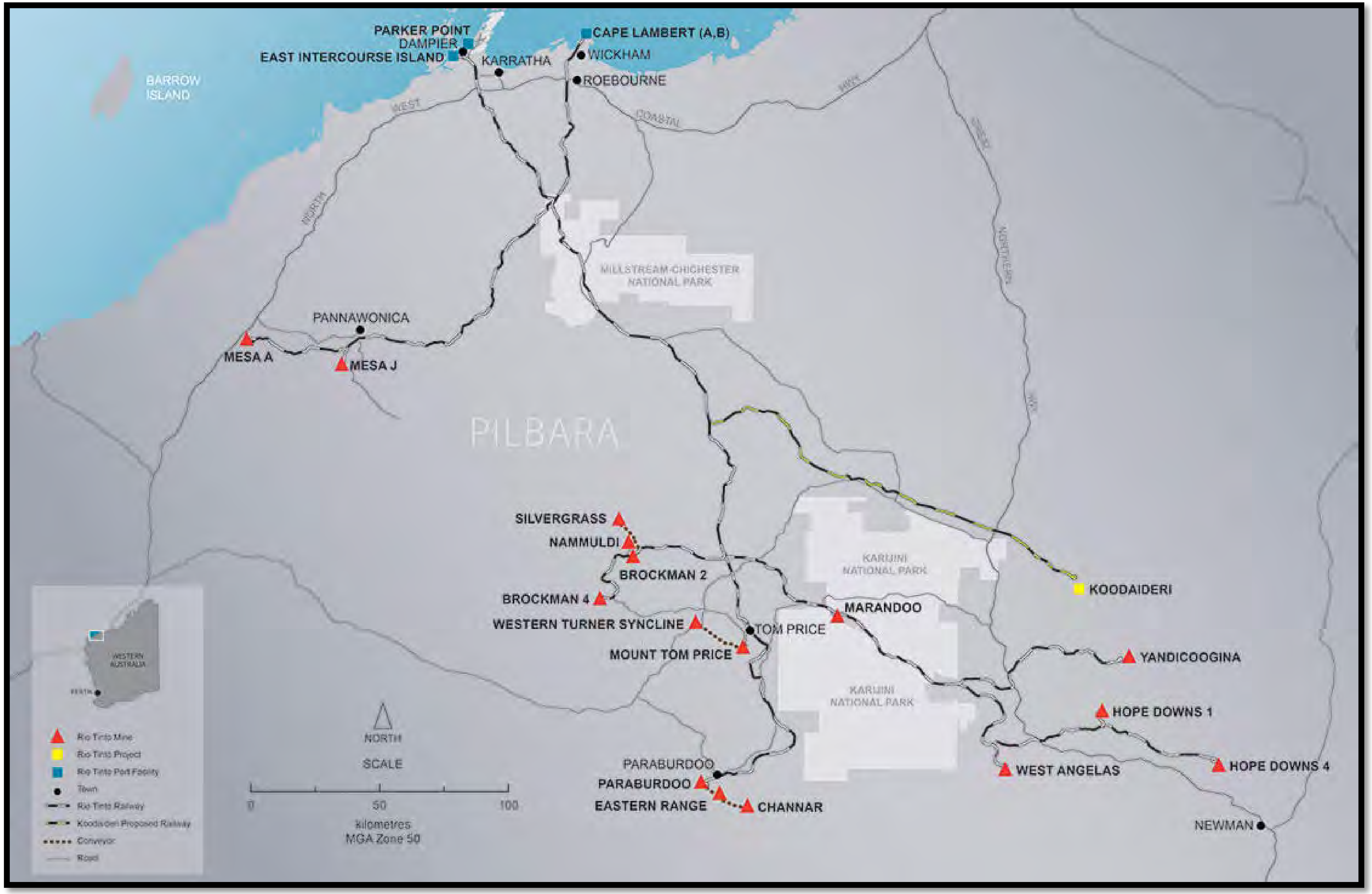
7. Innovative adaption of accepted practices

8. Turn research into implementable solutions

9. Validation of management systems

# Rio Tinto's Pilbara Mines




RioTinto

# Rio Tinto’s Pilbara Mines – PAF Material

- Historically, most Potentially Acid Forming (PAF) material has been mined from 1 or 2 mine sites per year
- More recently, PAF material is being mined from multiple mine sites

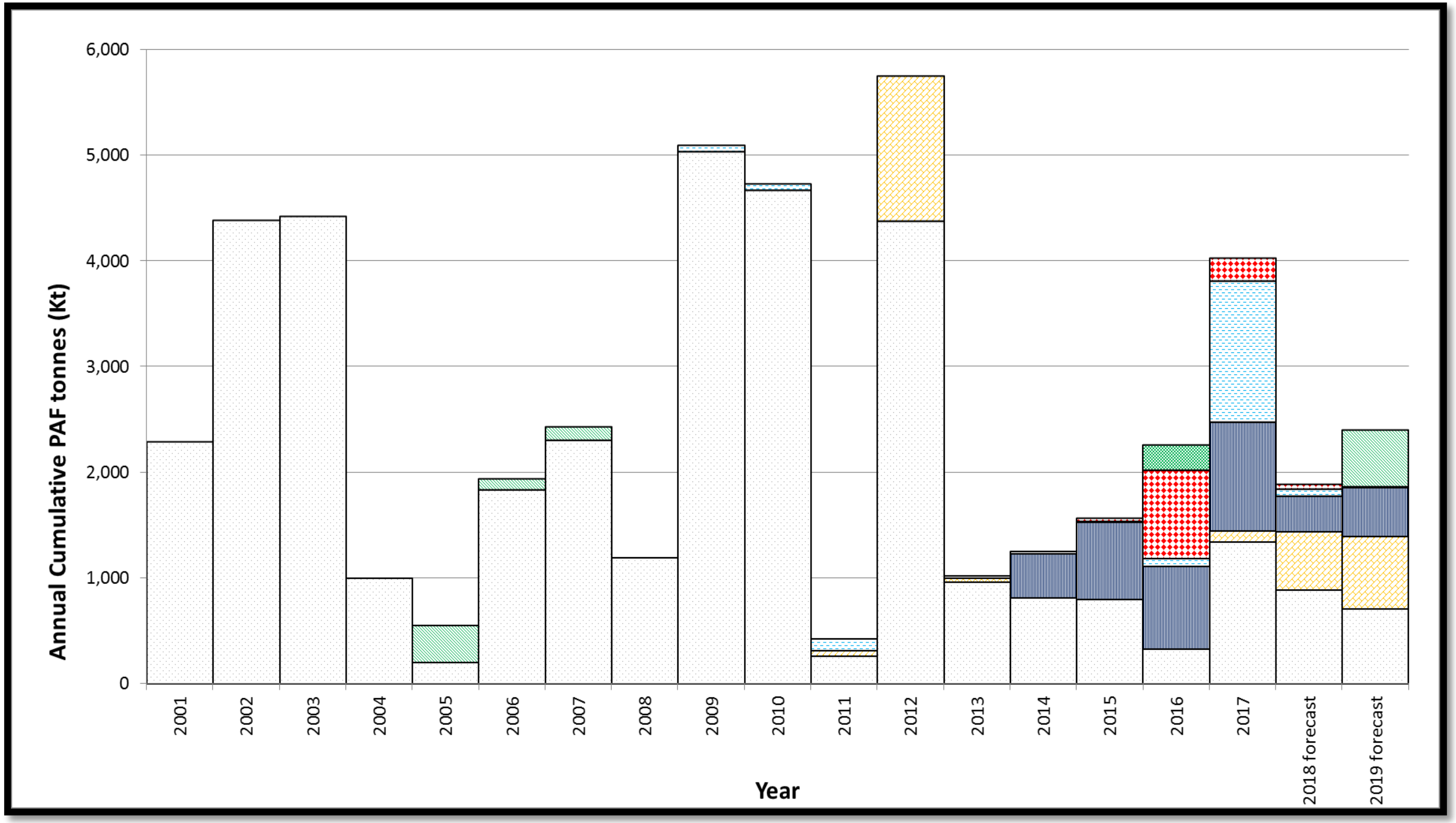



Figure: Annual PAF tonnages. Different colours represent different mine sites in the Pilbara

RioTinto

# Rio Tinto’s Pilbara Mines – PAF Material

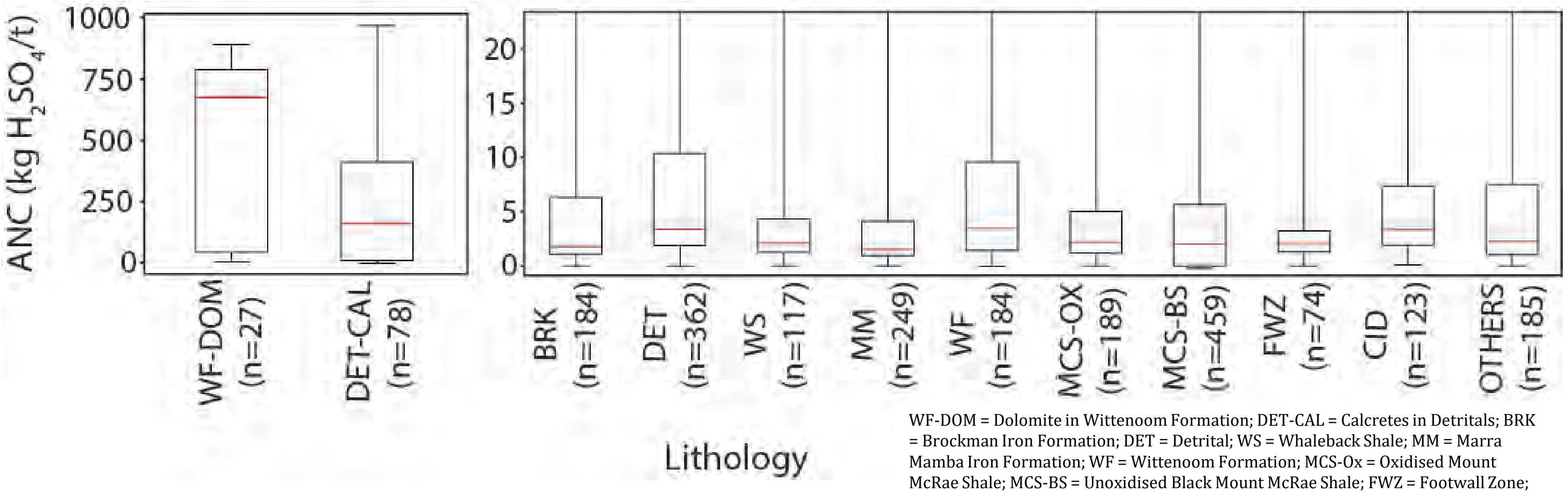
- PAF waste material is mined at some of Rio Tinto’s Pilbara mine sites
  - Pyrite-bearing ($FeS_2$) Mt McRae Black Shale, and lignites in detritals pose the greatest risk
- When excavated during mining, pyrite can oxidise, triggering the generation of heat and Acid and Metalliferous Drainage (AMD), with potential for spontaneous combustion

# Case Studies

# 1. Sound Science

## Case Study: Early orebody knowledge

- Regular acid base accounting and kinetic studies
- Segregation within geological and mining models
- AMD risk assessments




WF-DOM = Dolomite in Wittenoom Formation; DET-CAL = Calcretes in Detritals; BRK = Brockman Iron Formation; DET = Detrital; WS = Whaleback Shale; MM = Marra Mamba Iron Formation; WF = Wittenoom Formation; MCS-Ox = Oxidised Mount McRae Shale; MCS-BS = Unoxidised Black Mount McRae Shale; FWZ = Footwall Zone; CID = Channel Iron Deposits

Figure: Acid Neutralising Capacity (ANC) variation (5th percentile, 25th percentile, median, 75th percentile and 95th percentile) in different lithologies (showing the number of samples analysed)

# 2. Evaluation and Prioritisation of Risk

## Case Study: Identification of opportunities to manage or avoid AMD before mining

- PAF material on the pit shell was predicted during the study phase
- Uncertainty due to gaps in drilling data were assessed
- AMD risk assessment was completed
- Mine plans for each development project were revised to avoid or minimise exposing PAF material.
- This reduced the likelihood that acidic pit lakes would need to be managed in perpetuity.

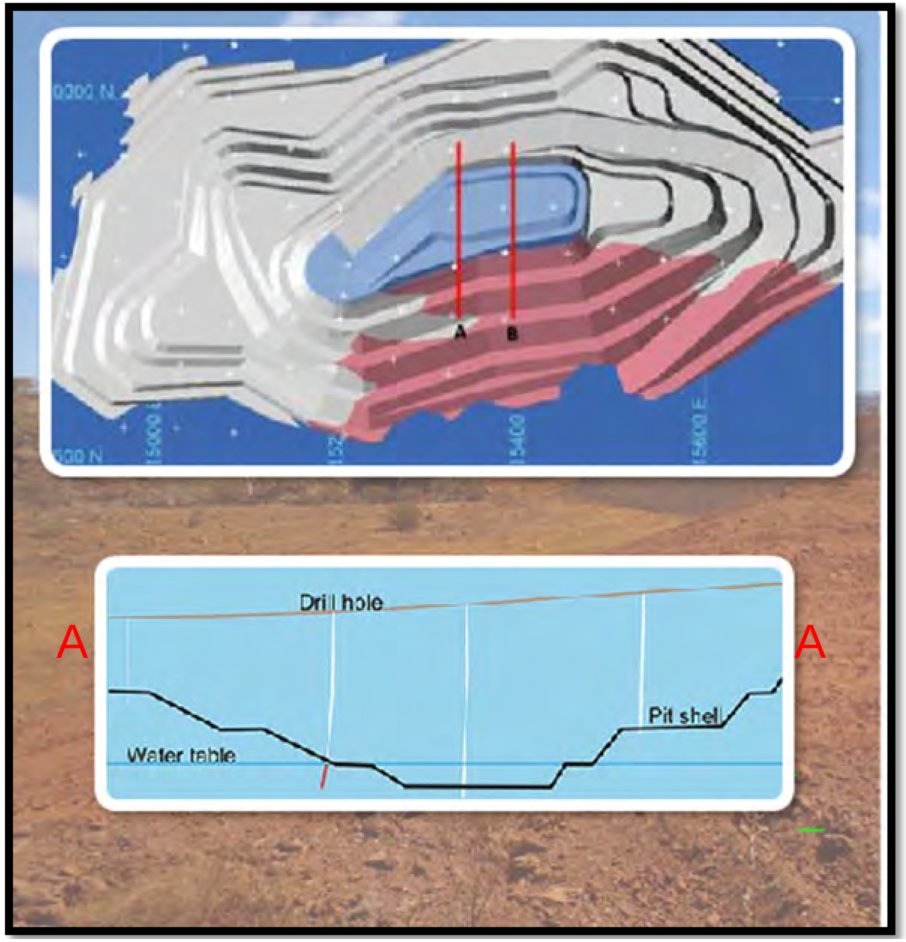



Figure: Pit outline and cross section (showing elevated sulfur material as red within the drill hole)

# 3. Transparency, Collaboration and an Ability to Work and Share Learnings (1)

## Case Study: Internal engagement

- Interactive mineral waste training module completed 400 times since 2014, primarily by Geologists, Hydrogeologists and Mine Planners
- Face to face and site specific operator training

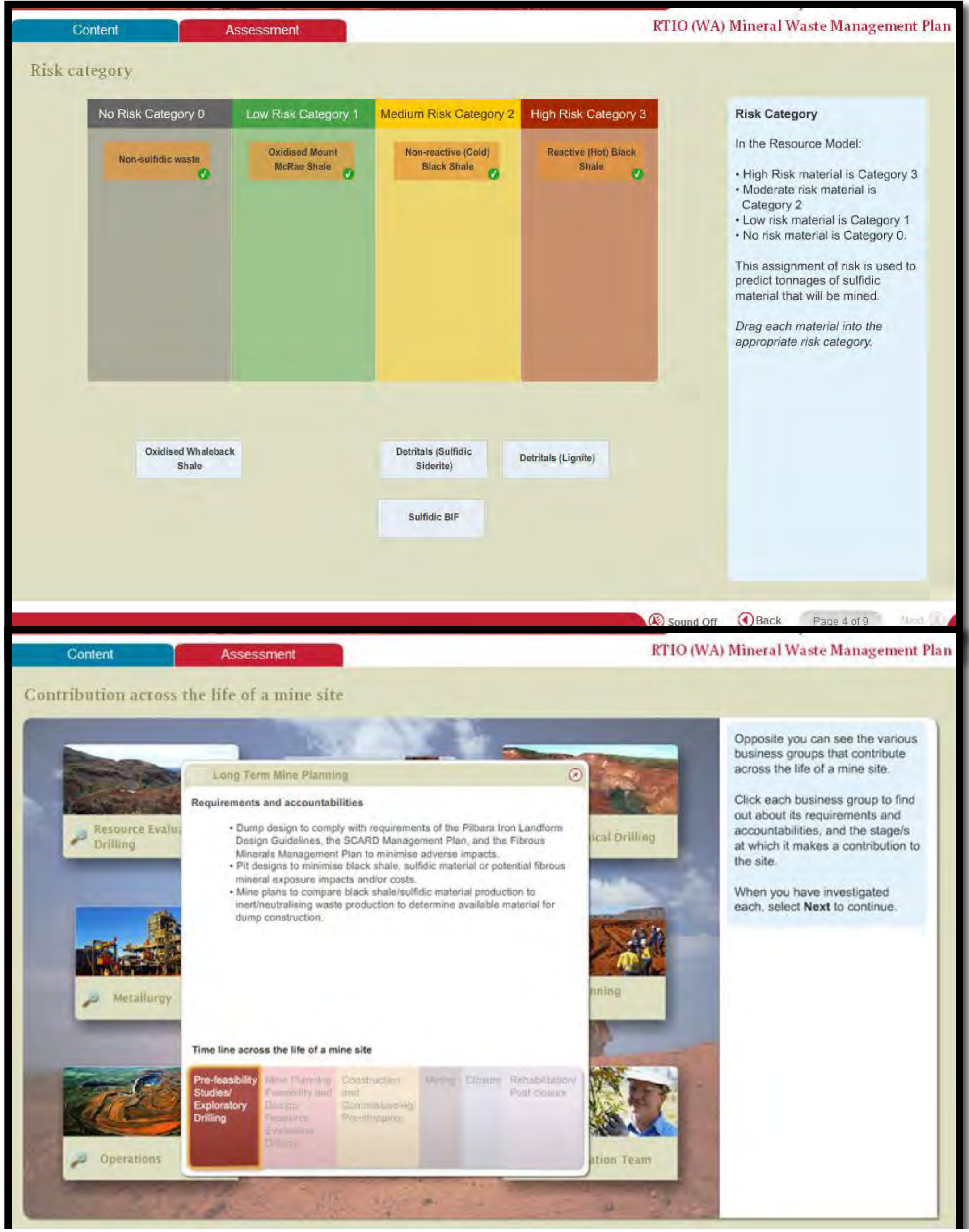



Figure: Exerts from the interactive mineral waste training module

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# 3. Transparency, Collaboration and an Ability to Work and Share Learnings (2)

## Case Study: External engagement

**Routine XRF**

**Objective:** Identify potential contaminants in a wide range of samples from different locations and depths

Elevated Sulfur

**Acid base accounting and kinetic test work**

Low Sulfur

**Extra elemental analysis of the solid and liquid extracts**

Evaluate waste storage options

**Objective**: Assess leachability as a function of conditions

### Modified Leach Extract Tests

**NAG leach**

**Mild acid/alkaline leach**

**Saline leach**

**Low water contact ratio**

**Multi-step leach**

**Geochemical interpretation**

Unresolved issues or uncertainty

**Objective:** Gain insight to the proportion of minor/trace element content that could be most vulnerable to mobilisation

**Objective:** Assessing reaction rates, relating leach potential to environmental setting

### Diagnostic Tests

**Detailed mineralogical test work**

**Sequential extractions**

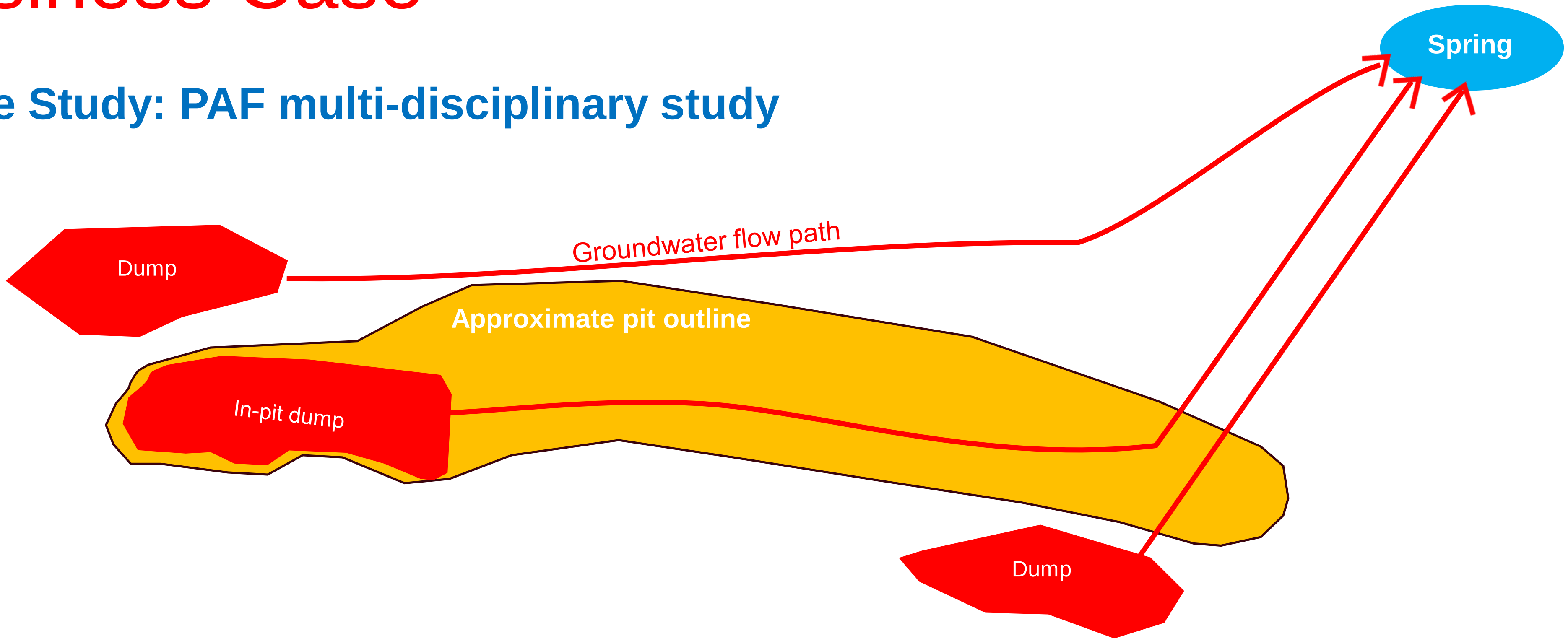
**Geochemical interpretation**

### Kinetic Tests, Other

**Free-draining or saturated column testing,**
**LEAF methodologies**

# 4. Management Practices that are Supported by a Business Case

## Case Study: PAF multi-disciplinary study




- Study undertaken in 2016 to identify the optimal PAF material storage location
- Consideration of environmental, compliance and business constraints
- An AWT dump far away from the Spring was selected because impact to the Spring would be negligible

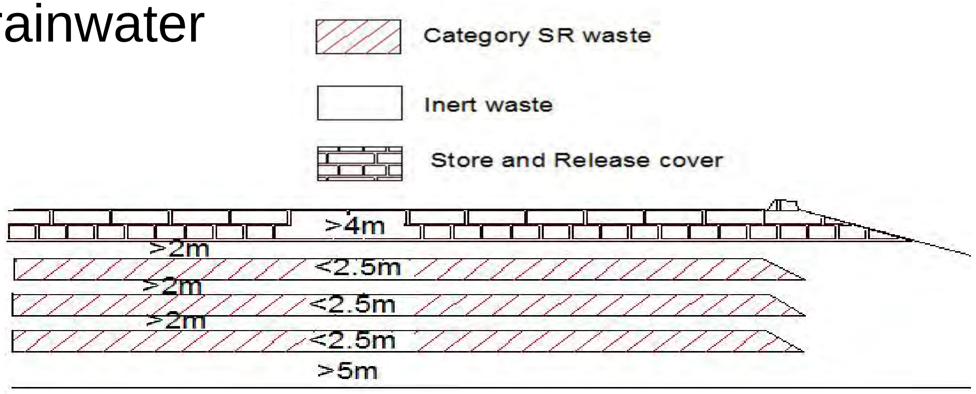
RioTinto

# 5. Long-term Environmentally Protective Management Practices

## Case Study: Building waste rock dumps to control spontaneous combustion and AMD

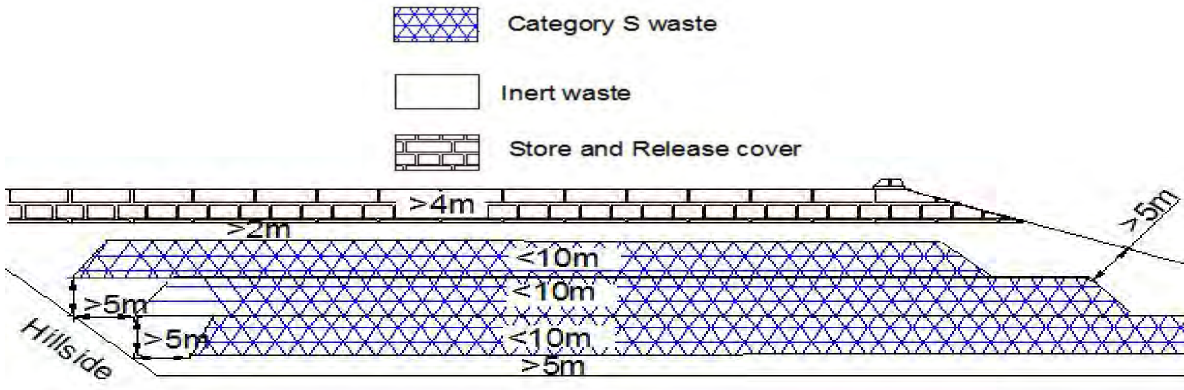
Reactive PAF material:

- Thin lift, base up dump construction for reactive materials
- Paddock dumped and compacted to limit air entry and optimise moisture retention
- Inert layer between reactive layers to dissipate heat
- Store and release cover to limit net percolation of rainwater




Non-reactive PAF and carbonaceous material:

- Encapsulation with inert waste during construction
- Stockpiling PAF material together to reduce oxidation rates
- Store and release cover to limit net percolation of rainwater



# 6. Strive to Improve Environmental Performance

## Case Study: External expert reviews of PAF management strategies

Business conformance audits:

- Business conformance audits assess conformance with Rio Tinto HSEC performance standards
- Senior personnel from within Rio Tinto undertake these reviews, particularly from different business units
- The E13 Chemically Reactive Mineral Waste Standard is 1 of the 5 Rio Tinto Standards that is reviewed

AMD/Mineral waste reviews

- AMD reviews are undertaken for necessary sites every 4 years
- Both external and internal AMD experts are utilised

RioTinto

# 7. Innovative Adaption of Accepted Practices

Figure: Mesocosims

## Case Study: Acidic pit lake bioremediation field trial

- Sulfate Reducing Bacteria (SRB), have the potential to remediate AMD by converting sulfates to sulfides under low redox environments while utilising labile organic carbon substrates as electron donors.
- 27 bales of hay (19t) added to an acidic pit lake. ≈ 0.3m thick layer across sediment
- pH levels increased and dissolved oxygen and sulfate decreased in deep waters. This may be attributed to SRB activity following hay deposition.
- The trial would need to run for a longer period to evaluate long-term viability.
- Controlled mesocosims were run in the laboratory and show promise for long-term viability.

Figure: Adding hay into an acidic pit lake

# 8. Turning Research into Implemental Solutions

## Case Study: Using GIS to make information widely available and assist make informed decisions on rehabilitation, backfill and monitoring needs

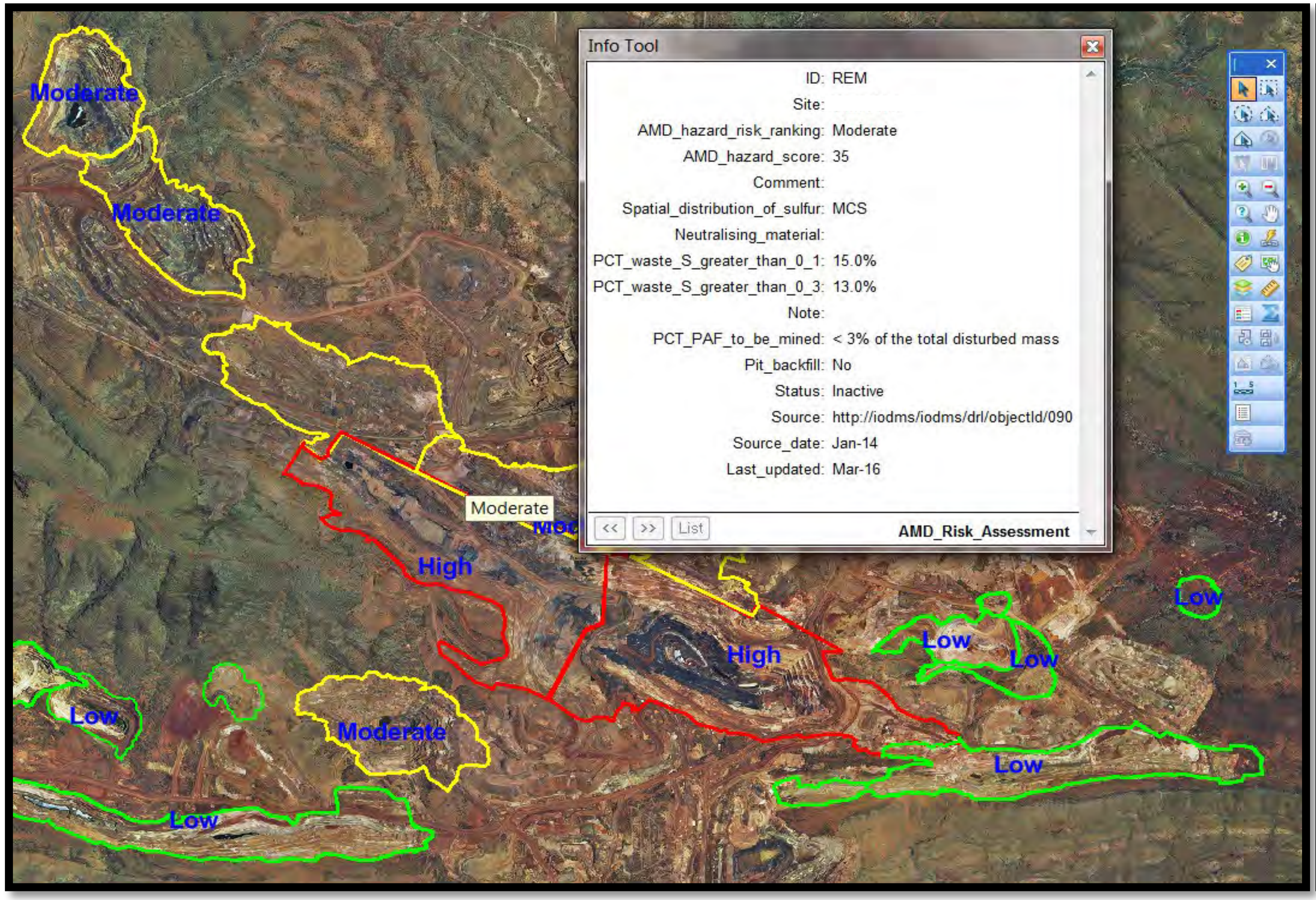



Figure: Assigned AMD risk of pits of either low, moderate or high.

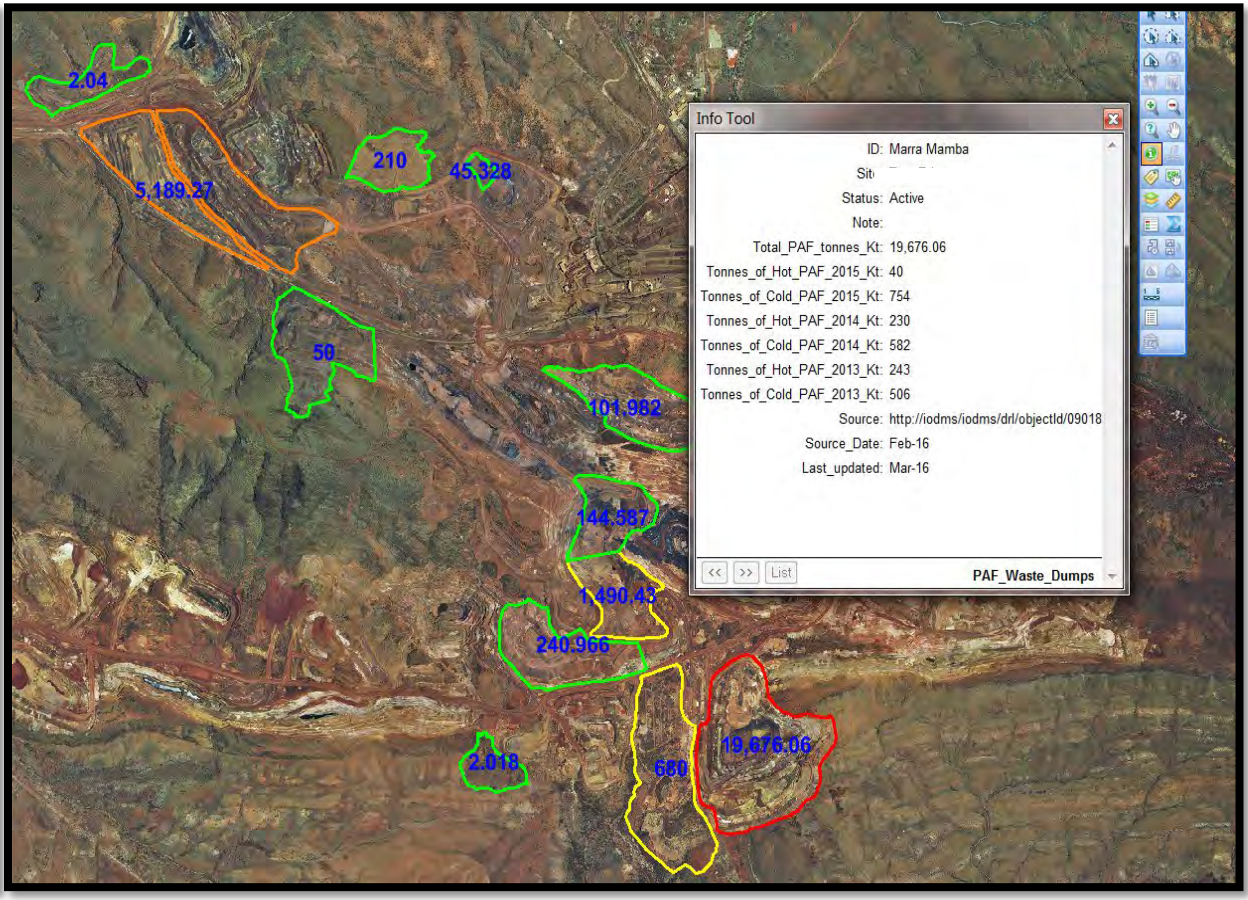
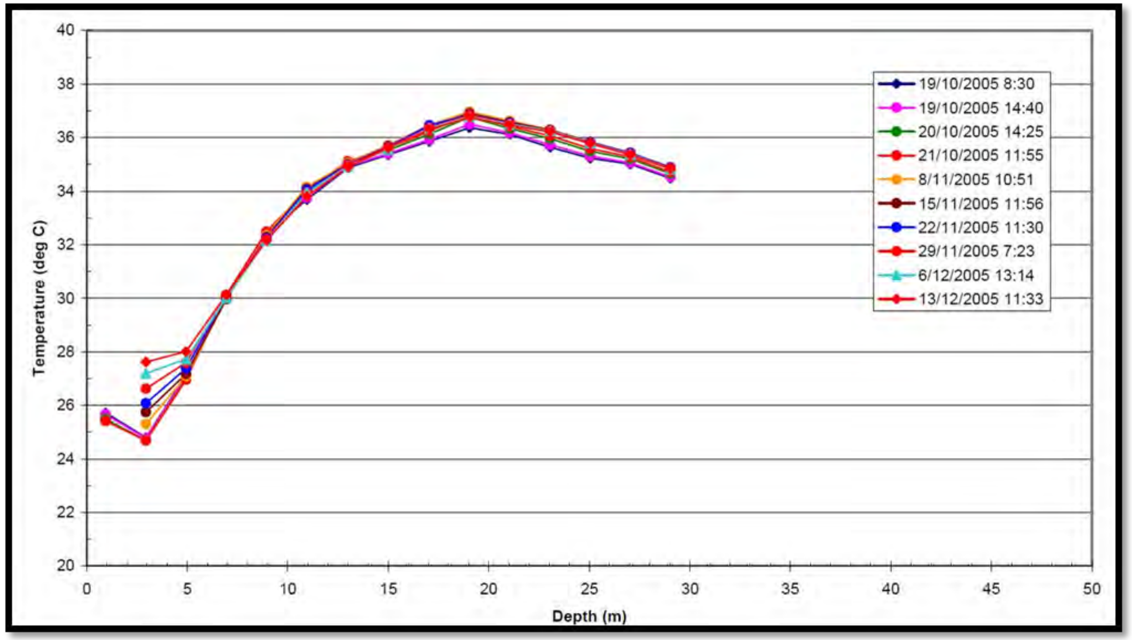



Figure: PAF waste dump locations and estimated PAF tonnages.

# 9. Validation of Management Systems

## Case Study: Waste dump design verification

- Drilled 3 historical PAF waste rock dumps
- Study concluded that the dumping strategy was effective in controlling spontaneous combustion
- Maximum temperature was 55$^o$C which confirms no combustion of black shale in the monitoring regions



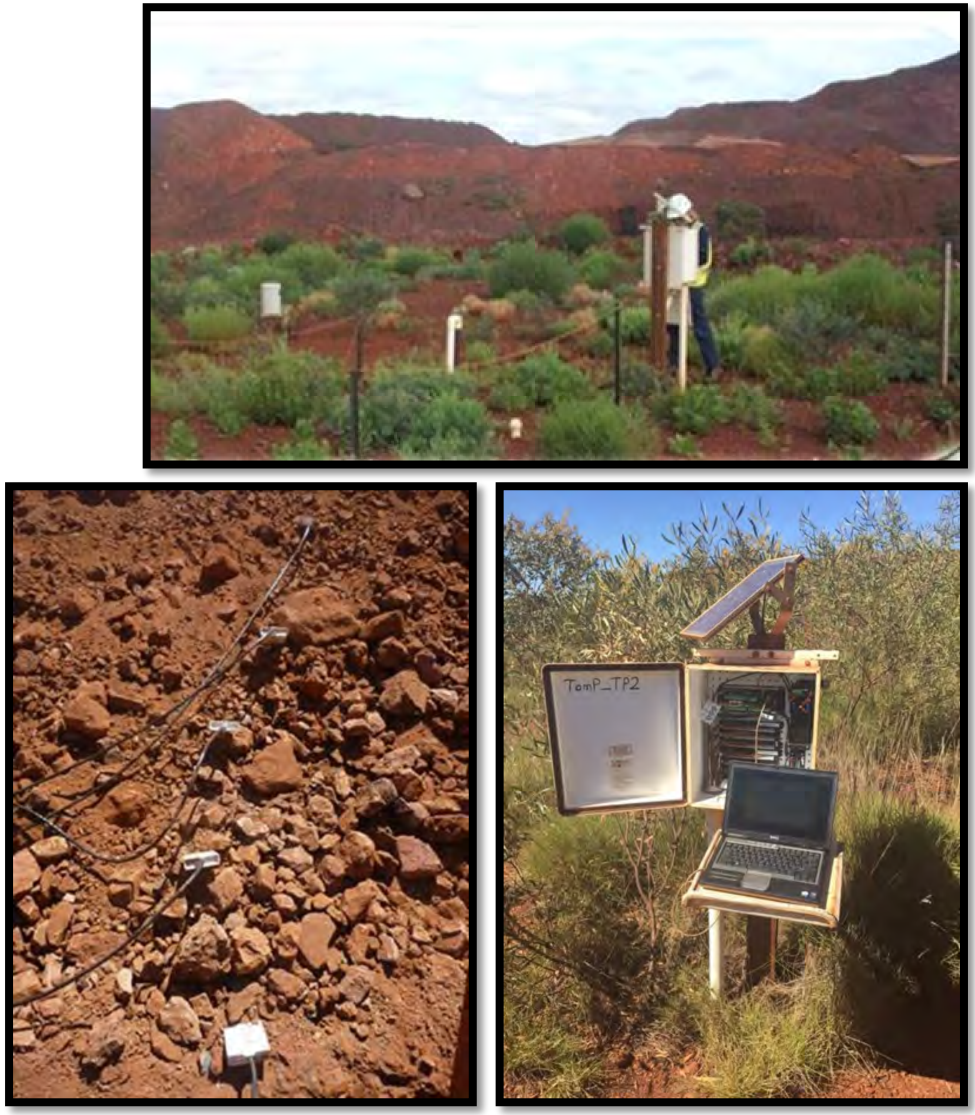

Figures: Temperature monitoring within PAF waste rock dumps

# Conclusions

The mineral waste strategy for Rio Tinto’s Pilbara mines aim to:

- Ensure accurate valuation of projects, acquisitions, and expansions
- Reduce environmental and health risk
- Reduce operational costs
- Reduce closure costs
- Enhance business reputation

This is done through applying the strategy principles, via multiple systems, management plans, awareness and collaboration



Figures: Monitoring of covers and waste rock dumps

The University of Queensland
Australia
CREATE CHANGE

# Targeted metal recovery during simultaneous treatment of acid mine drainage

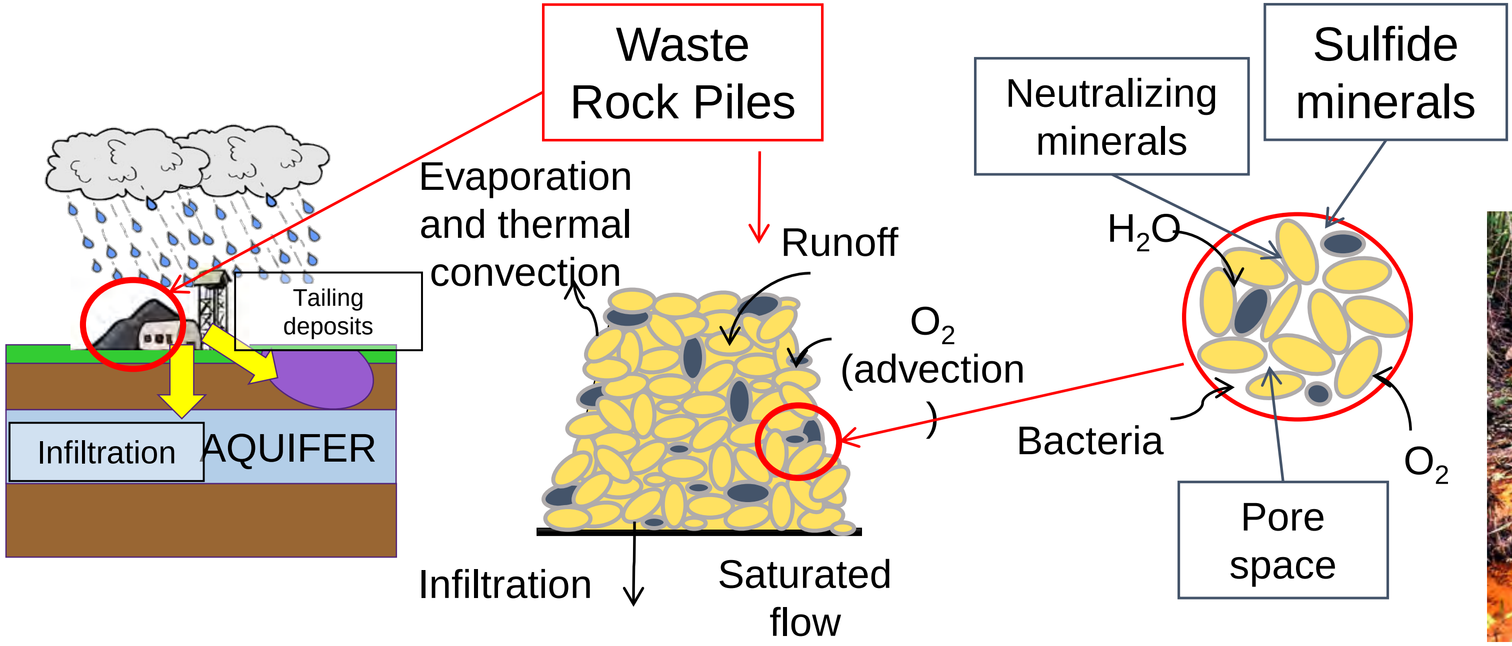
**Emma Thompson-Brewster[a,b], Luke Berry[a], Stefano Freguia[c], Mansour Edraki[b] and Pablo Ledezma[c]**

[a] Kinetic Group Worldwide Pty Ltd, Australia

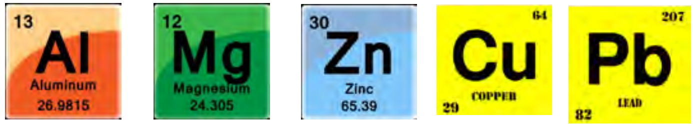
[b] Centre for Mined Land Rehabilitation, Sustainable Minerals Institute, The University of Queensland, Australia

[c] Advanced Water Management Centre, The University of Queensland, Australia

# Acid mine drainage (AMD)




$$FeS_{2(S)} + \tfrac{7}{2}O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2\,H^+$$
$$Fe^{2+} + \tfrac{1}{4}O_2 + H^+ = Fe^{3+} + \tfrac{1}{2}H_2O$$
$$Fe^{3+} + 3H_2O = Fe(OH)_{3(S)} + 3H^+$$

+ 

| Unit in mg/L | | Trigger values for freshwater* Level of protection (% species) | | | | Aquatic ecosystems* | Irrigation*' | Stock water* | Aquaculture* | Drinking water# | Visual recreation^† | Primary recreation^ | Secondary recreation^ | Farm use & | Industrial use ~ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ecosystem Protection Level | | HEV and SD | MD | | HD | | | | | | | | | | |
| Contaminant/Stressor | | 99% | 95% | 90% | 80% | Sediment | | | | | | | | | |
| Aluminium | pH>6.5 | 0.027 | 0.055 | 0.08 | 0.15 | ND | | | | | | | | | |
| | pH<6.5 | 0.0008 | 0.0008 | 0.0008 | 0.0008 | ND | | | | | | | | | |
| Cadmium | H | 0.00006 | 0.0002 | 0.0004 | 0.0008 | 1.5 | 0. | | | | | | | | |
| Cobalt | | 0.00014 | 0.00014 | 0.00014 | 0.00014 | ND | 0. | | | | | | | | |
| Copper | H | 0.001 | 0.0014 | 0.0018 | 0.0025 | 65 | 0 | | | | | | | | |
| Iron | | ND | ND | ND | ND | ND | 0 | | | | | | | | |
| Lead | H | 0.001 | 0.0034 | 0.0056 | 0.0094 | 50 | | | | | | | | | |
| Manganese | | 1.2 | 1.9 | 2.5 | 3.6 | ND | 0 | | | | | | | | |
| Uranium | | 0.0005 | 0.0005 | 0.0005 | 0.0005 | ND | 0. | | | | | | | | |
| Zinc | H | 0.0024 | 0.008 | 0.015 | 0.031 | 200 | | | | | | | | | |
| Cyanide | | 0.004[g] | 0.007[g] | 0.011[g] | 0.018[g] | 0.1[k] | N | | | | | | | | |
| Sulfate | | 20th, 50th and 80th percentile of reference data | 80th percentile of reference data | 80th percentile of reference data | 10th and 90th percentile of reference data | ND | N | | | | | | | | |
| pH (pH units) | | 20th, 50th and 80th percentile of reference data | 20th and 80th percentile of reference data | 20th and 80th percentile of reference data | 10th and 90th percentile of reference data | ND | N | | | | | | | | |
| conductivity | | ND | ND | ND | ND | ND | 0.6 - dS depe on cr soil | | | | | | | | |
| Total dissolved solids | | 20th, 50th and 80th percentile of reference data | 80th percentile of reference data | 80th percentile of reference data | 80th percentile of reference data | ND | N | | | | | | | | |

*From ANECC 2000

#From Australian Drinking Water Guidelines 2011

^From NH&MRC Guidelines for managing risk in recreational waters, 2008

*Contact Recreational Use: based on a multiple of 10 times the drinking water criteria, consistent with the advice given in the NH&MRC Guidelines for managing risk in recreational waters, 2008.*

*Non-contact Recreational Use (namely Visual Use): should refer to narrative criteria in the NH&MRC Guidelines for managing risk in recreational waters, 2008.*

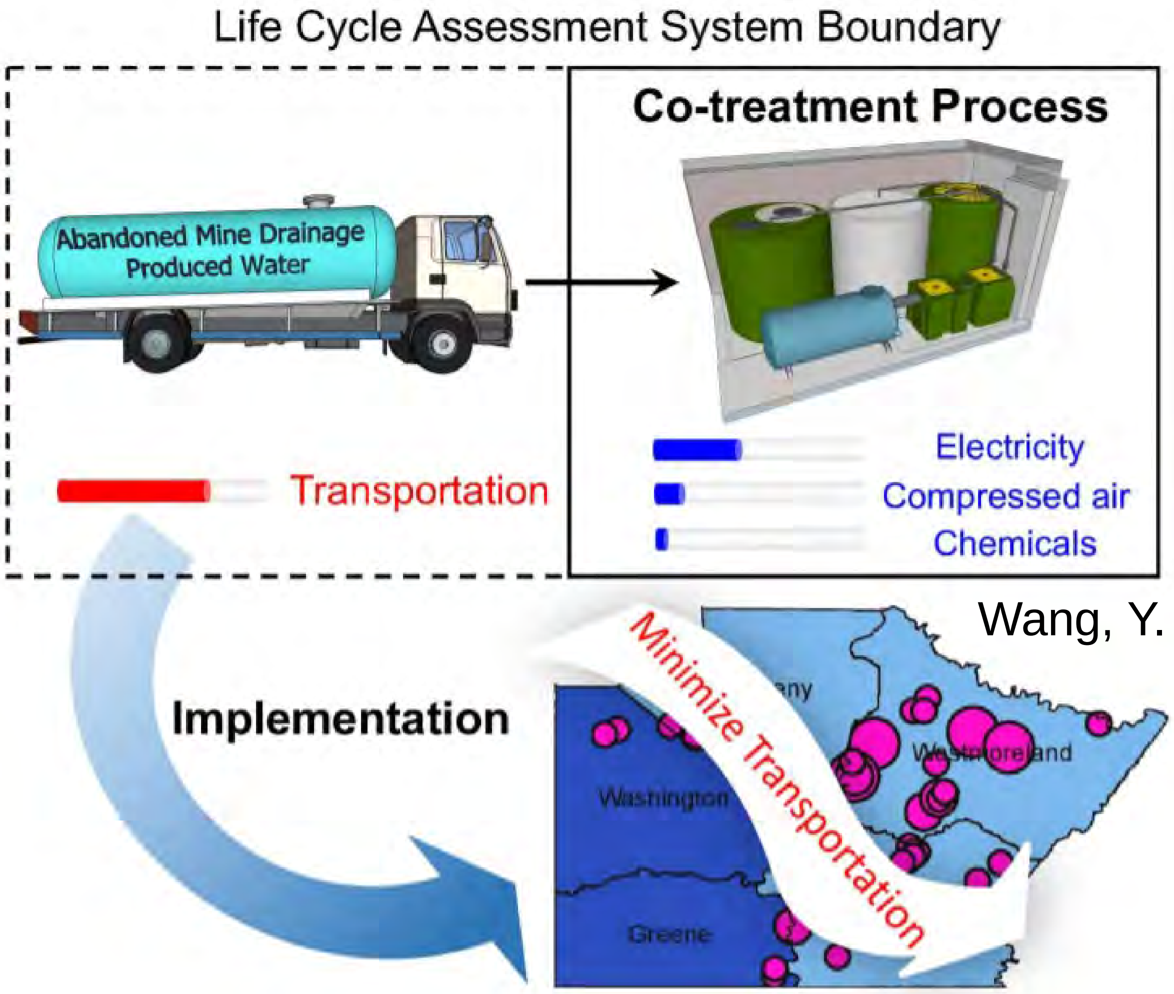
†Narrative criteria for the visual aesthetic parameters: Transparency and colour; oil, grease and detergents; litter; Odour; Noise

Guideline: *Recreational water bodies should be aesthetically acceptable to recreational users. The water should be free from visible materials that may settle to form objectionable deposits; floating debris, oil, scum and other matter; substances producing objectionable colour, odour, taste or turbidity; and substances and conditions that produceundesirable aquatic life.*

&Refer to irrigation and drinking water guidelines

~No guidelines are provided in ANZECC 2000, and the guidelines vary according to the industry and this value is usually protected by other values, such as aquatic ecosystem.

dLead values related to hardness: 0.001mg/L at0–60 mg CaCO3/L ; 0.002mg/L at 60–120 mg CaCO3/L; 0.004 mg/L at 120-180 mg CaCO3/L; 0.007 mg/L at>180 mg CaCO3/L.




Wang, Y. *et al. ES&T.* 2018

**Meeting discharge standards:**

~$100 m$^{-3}$ (irrespective of tech.)

# AMD: the incalculable cost of doing nothing

## Acid drainage: the global environmental crisis you've never heard of

A gold rush brings in lots of money in the short-term, but leaves a toxic legacy

Stephen Tuffnell | Wednesday 13 September 2017 23:00 | 13 comments

Like Click to follow The Independent

Colorado & Brazil mine disasters kill two rivers in 2015.


NASA Earth Observatory image shows toxic mud reaching Atlantic Ocean.

Mariana dam collapse, Minas Gerais, Brasil (2015)

Animas River in Colorado, USA (2015)

Brumadinho dam collapse, Minas Gerais, Brasil (2019)

# Acid mine drainage and legacy mine sites in Queensland

-15,000 legacy mines

- 300 classified as mega, large or medium size


ABC NEWS
LOCATION: Brisbane, Qld
Press F11 to exit full screen
Just In · Australia Votes · World · Business · Sport · Science · Health · Arts · Analy

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## Cyanide ponds from abandoned mine could spill into Murray-Darling Basin; farmers fear 'catastrophe'

Exclusive by the National Reporting Team's Mark Willacy and Courtney Wilson

Updated 29 Sep 2015, 9:30pm

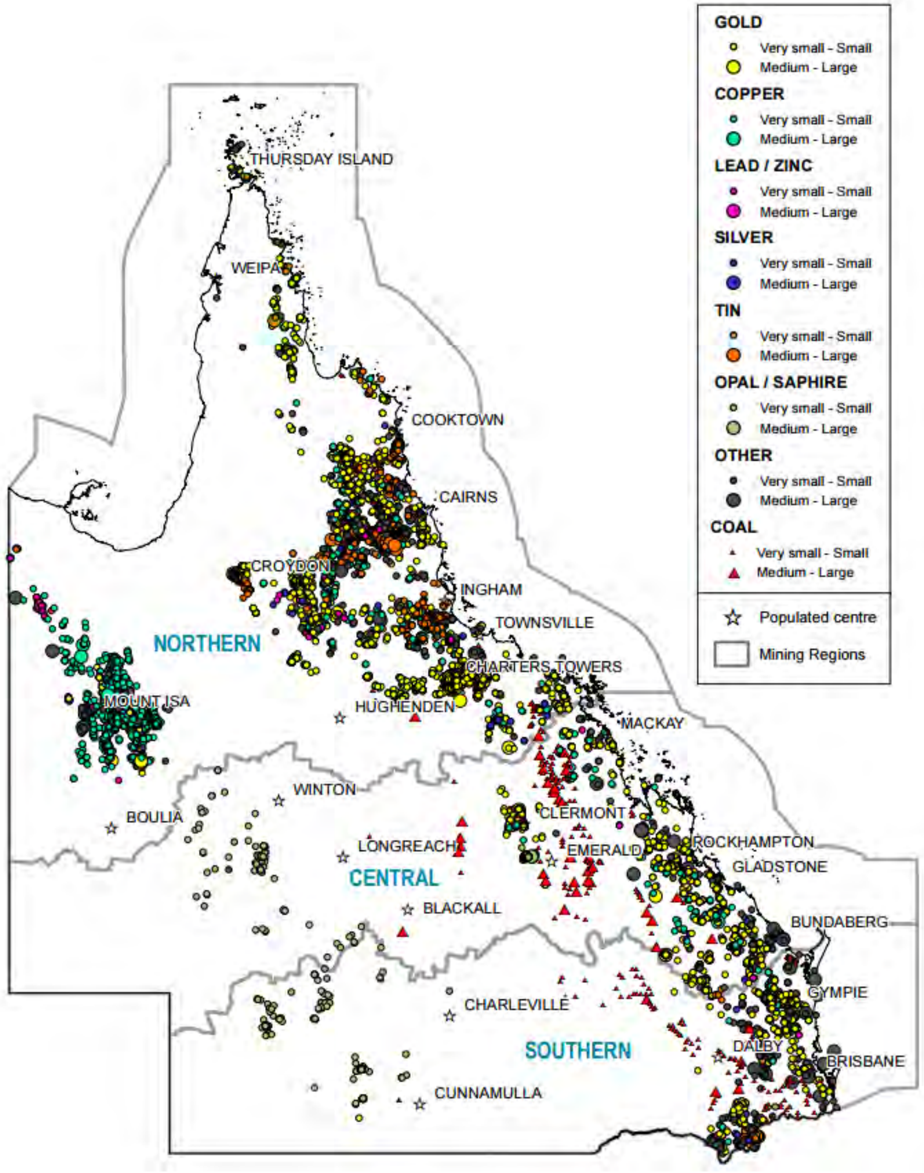


YOUTUBE: Toxic mining residue could be spilled into Murray-Darling Basin

**Queensland authorities fear a series of ponds containing heavy metals and cyanide could overflow from an abandoned mining site and spill into a nearby river in the Murray-Darling Basin.**

Overflow risk with only

40 mm of rain (!)



# Conventional chemical dosing & Biological sulfate removal

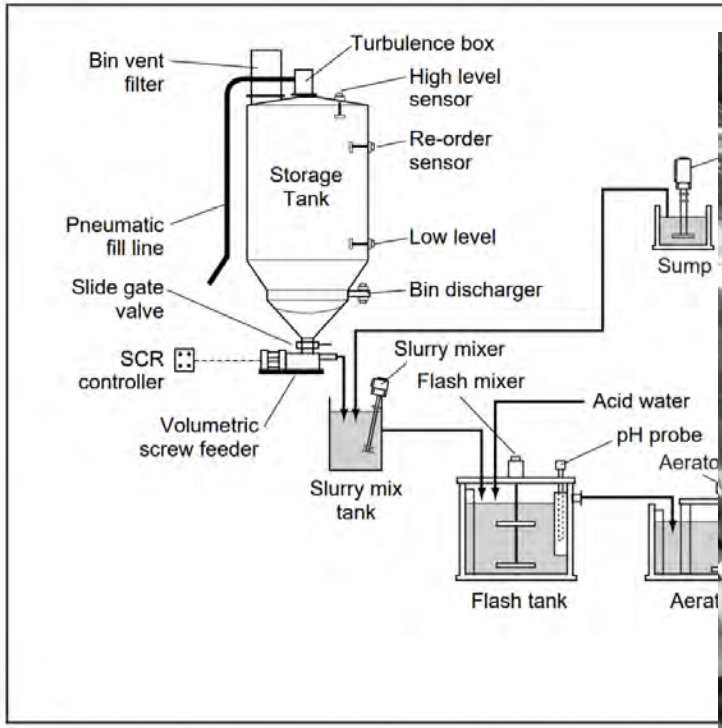


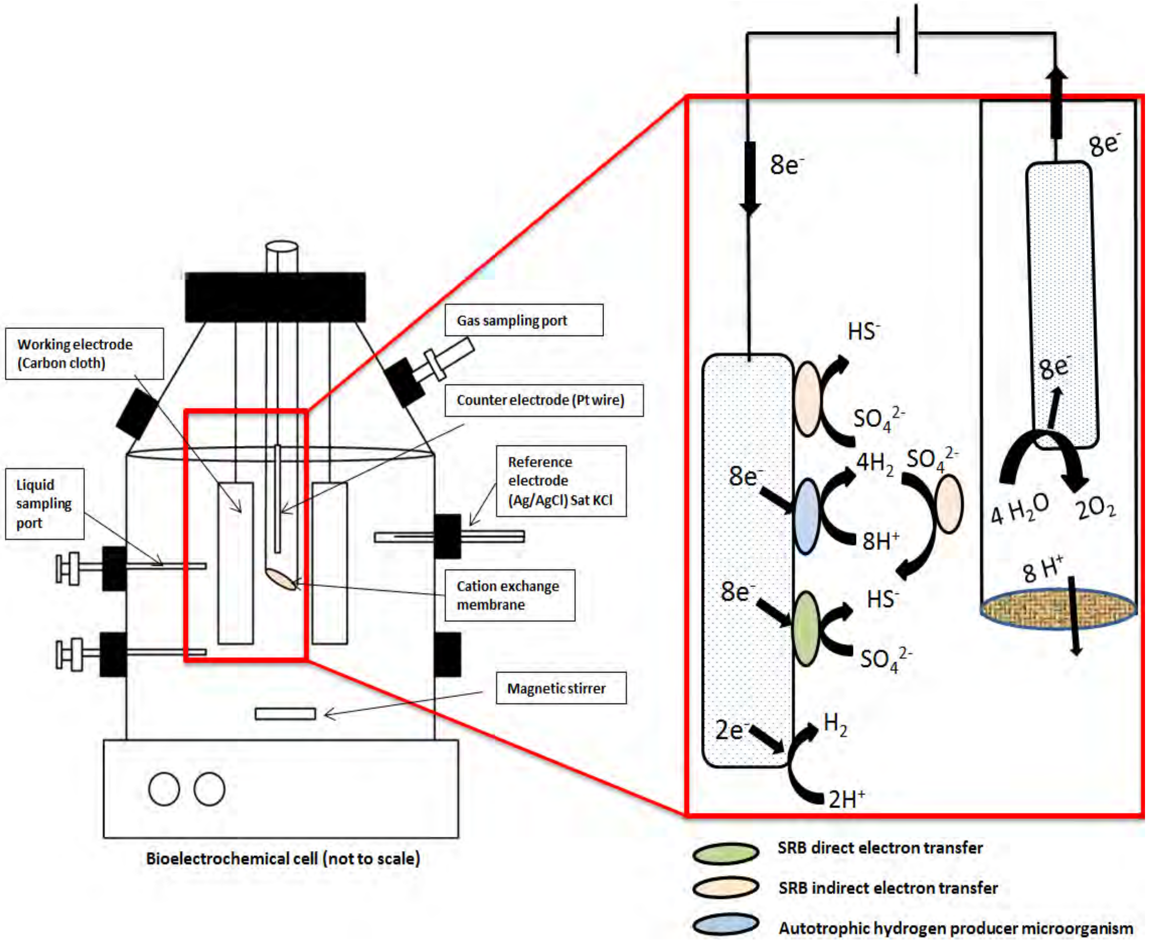

**Figure 4-2.** Conventional water treatment utilizing lime. (Source: http://amd.c

The primary offset to acid productio
is the consumption of acidity by calci

$CaCO_3 + 2H^+ = Ca^{2+} + CO_{2(G)} + H_2O$ (3-

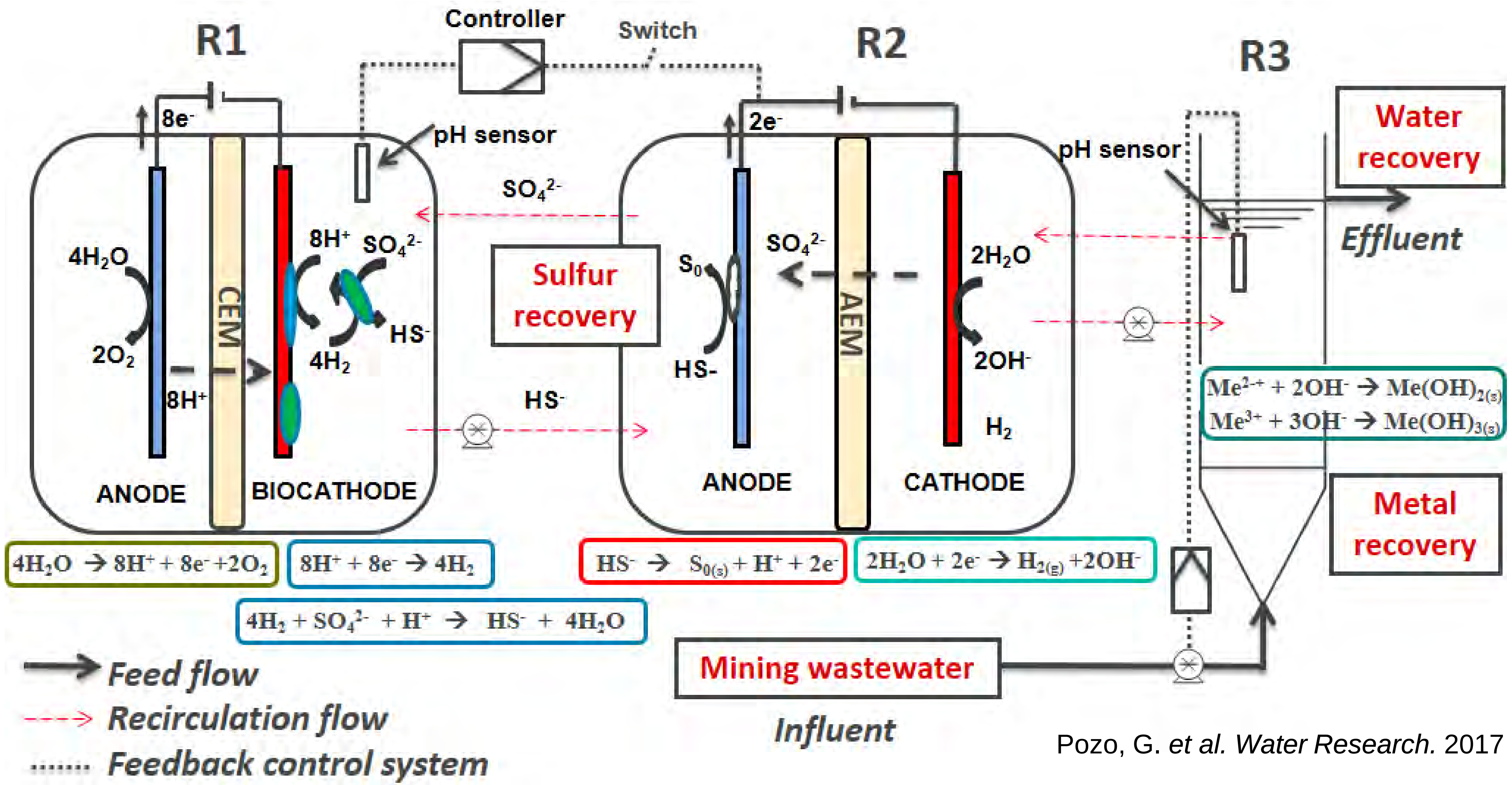
and precipitating sulfate as calcium sulfate ($CaSO_4$).

$SO_4 + Ca^{2+} = CaSO_{4(S)}$ (3-

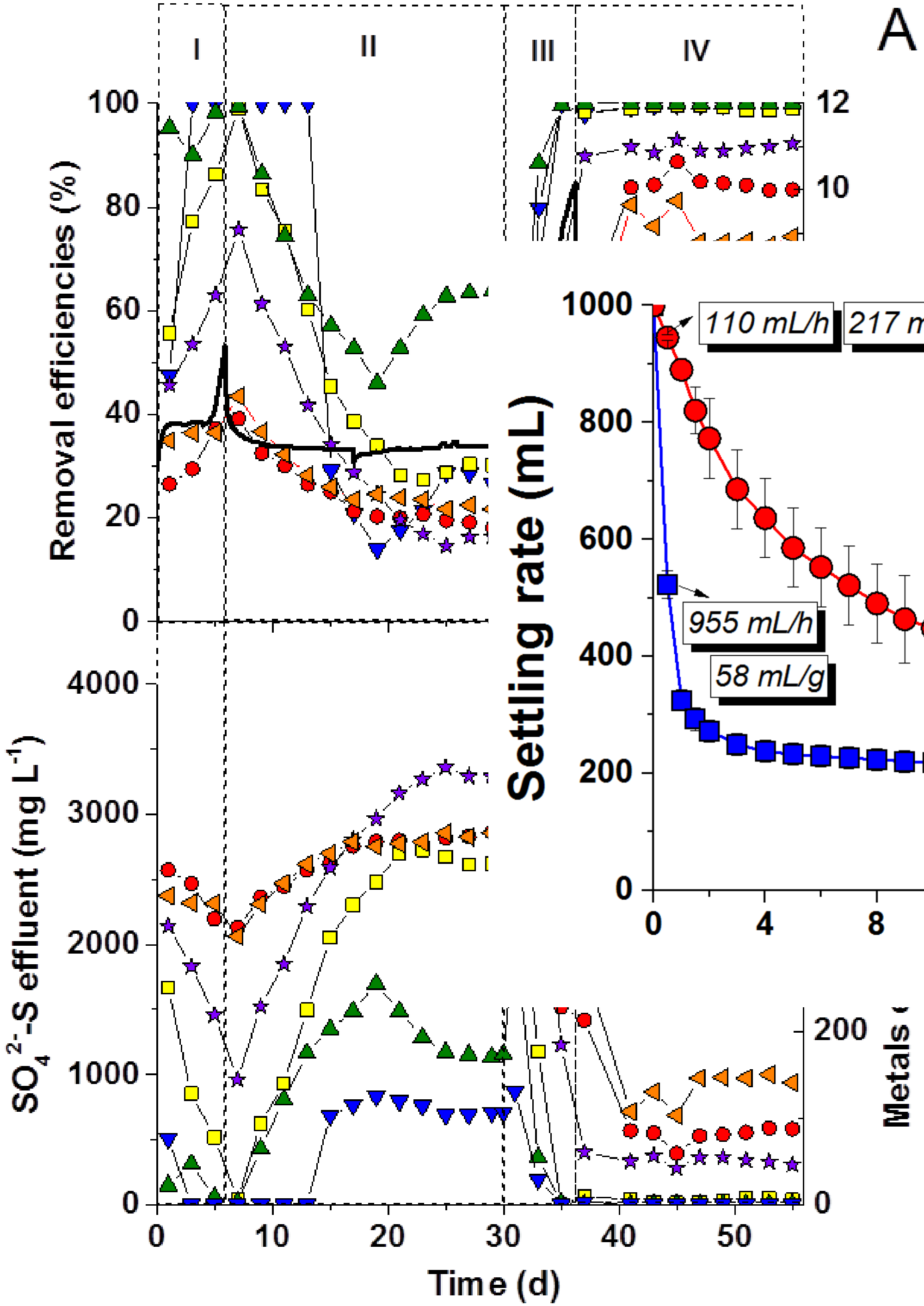



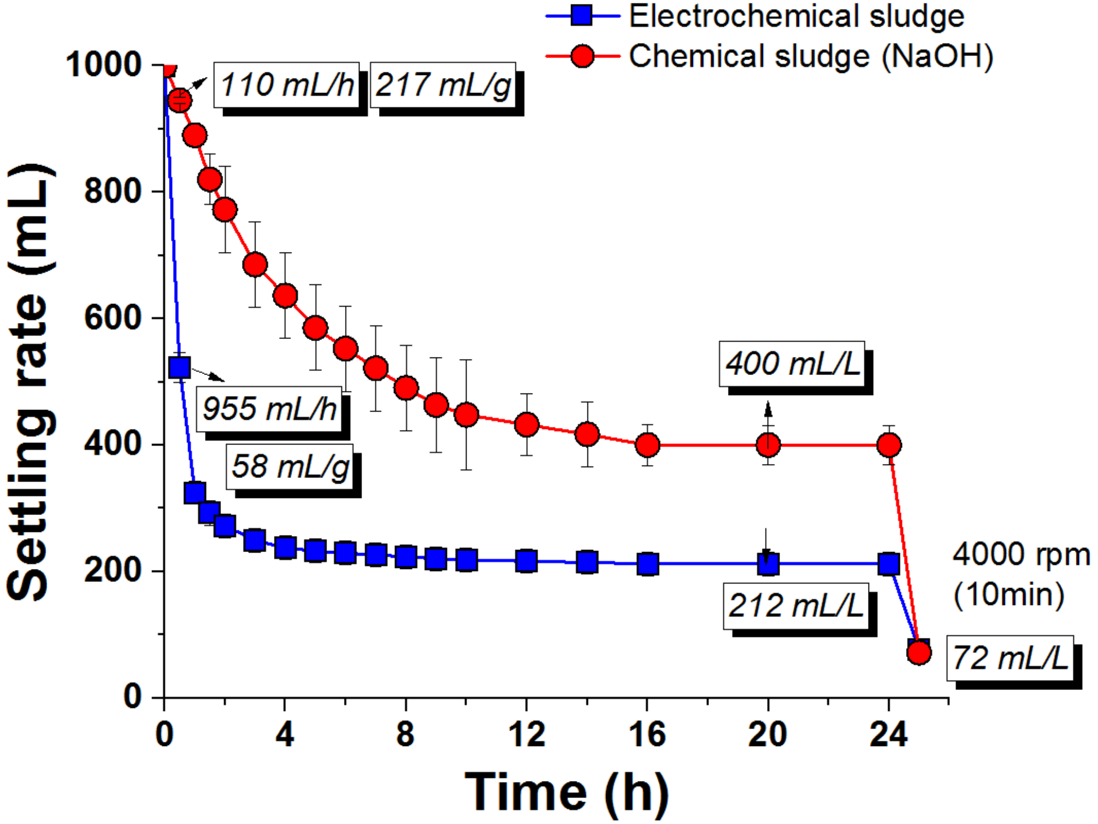

Pozo, G. *et al. Biolelectrochem.* 2017

# SULFRED: hybrid biological/electrochemical treatment of AMD

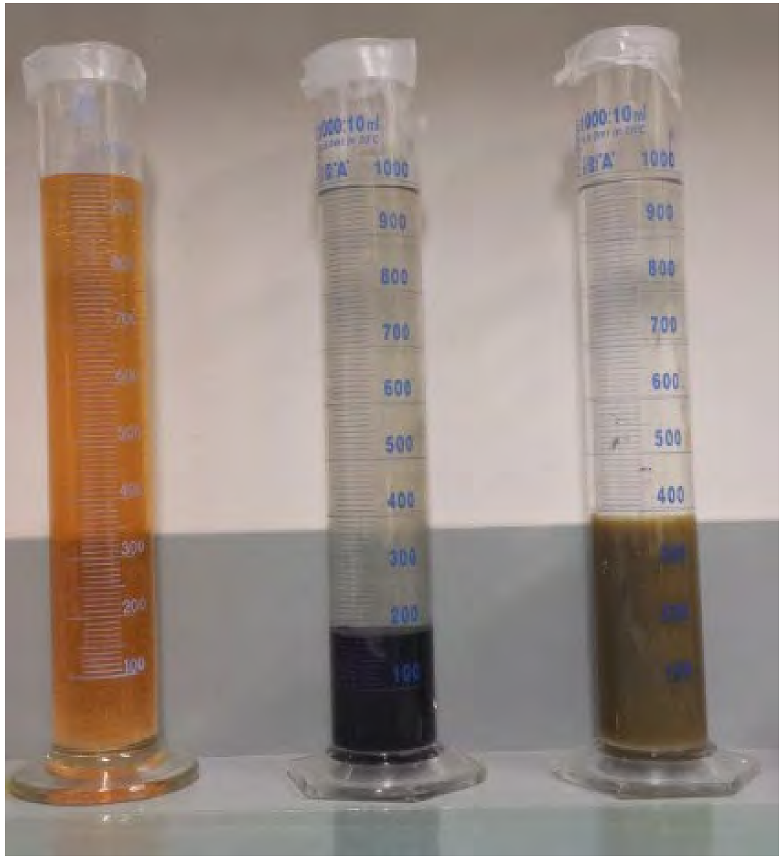



Pozo, G. *et al. Water Research.* 2017




Pozo, G. *et al. Water Research.* 2017



**AMD** **MES** **CHEM**

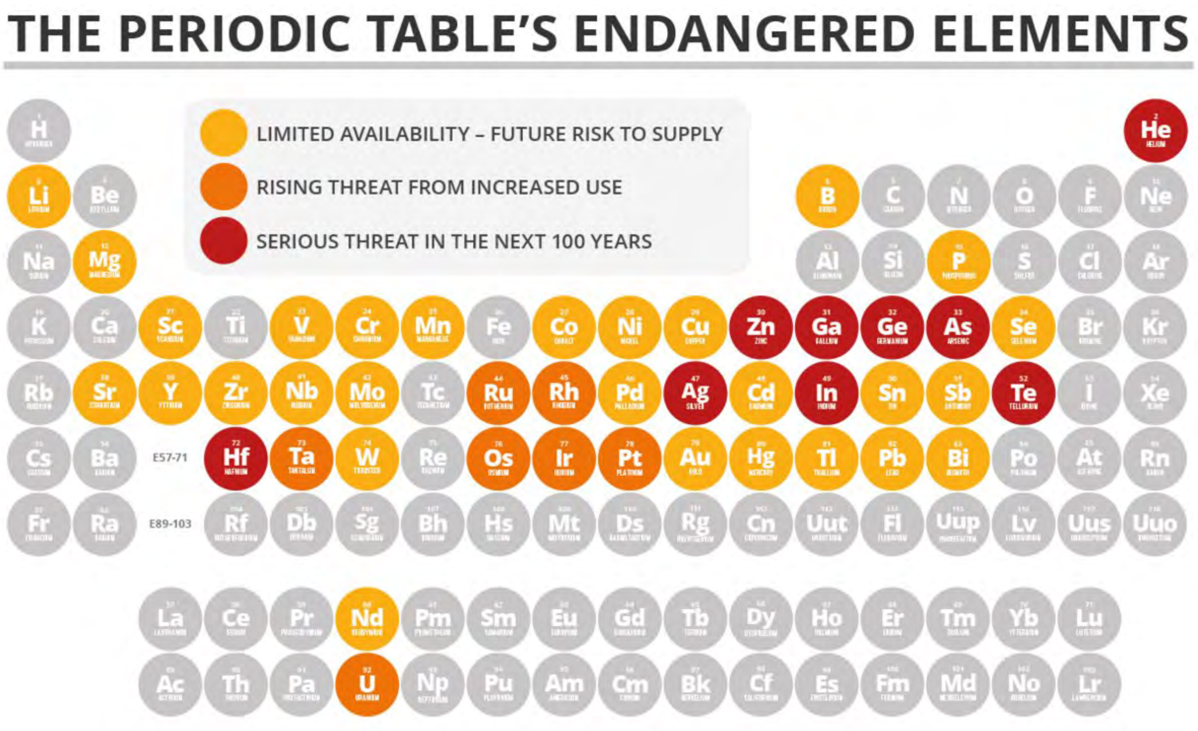
# Analysis of precipitates

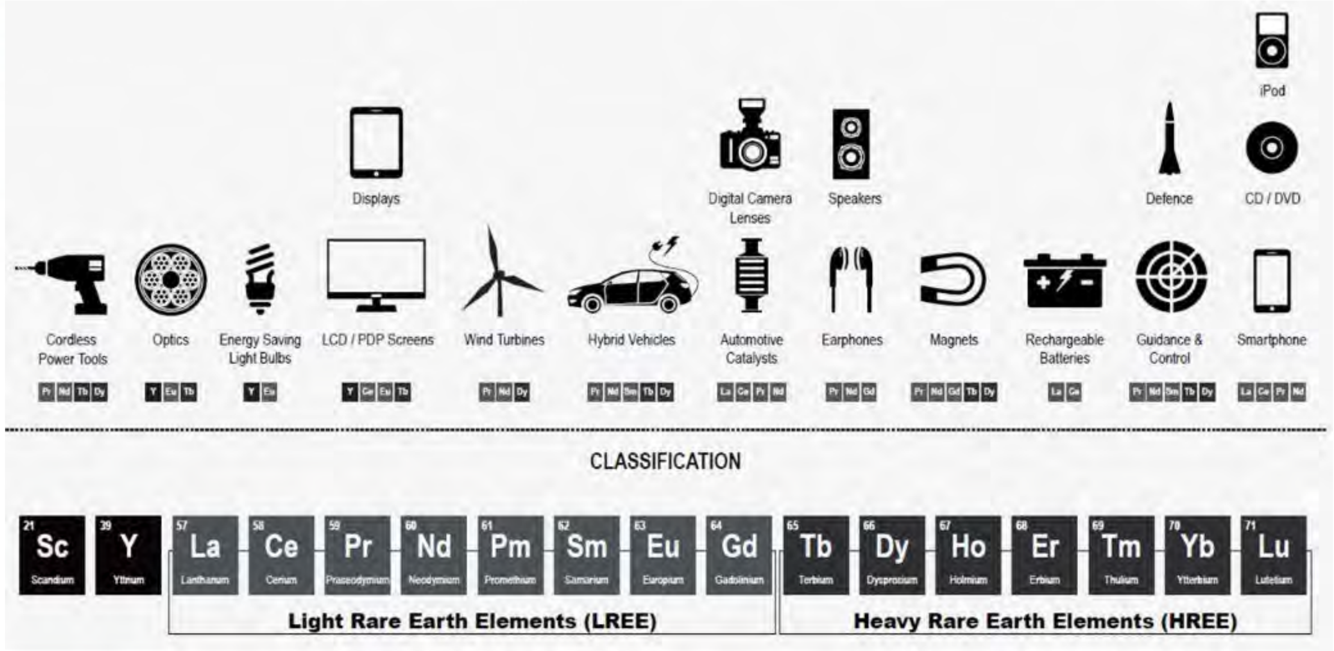
| Sample | Solid precipitate after MES treatment; final pH:7.3 | Solid precipitate after NaOH addition; final pH:7.3 |
|---|---|---|
| **Major metals (mg g$^{-1}$ solid precipitate)** | | |
| Al | 263 ± 2 | 220 ± 0 |
| As | 1.3 ± 0 | 1.6 ± 0 |
| Ca | 23 ± 0 | 27 ± 0 |
| Cd | 0.1 ± 0 | 0.1 ± 0 |
| Co | 2.7 ± 0 | 2.5 ± 0 |
| Cr | 0.3 ± 0 | 0.3 ± 0 |
| Cu | 4.5 ± 0 | 2.2 ± 0 |
| Fe | 279 ± 2 | 307 ± 1 |
| K | 2 ± 0 | 3.4 ± 0 |
| Mg | 152 ± 0 | 77 ± 1 |
| Mn | 27 ± 0 | 25 ± 0 |
| Na | 21 ± 0 | 67 ± 0 |
| Ni | 3 ± 0 | 2.4 ± 0 |
| P | 7 ± 1 | 2.7 ± 0 |
| S | 123 ± 25 | 126 ± 2 |
| Zn | 90 ± 0 | 74 ± 0 |

| Sample | Solid precipitate after MES treatment; final pH:7.3 | Solid precipitate after NaOH addition; final pH:7.3 |
|---|---|---|
| **Rare earth elements + yttrium (µg g$^{-1}$ solid precipitate)** | | |
| Y | 498 ± 70 | 415 ± 16 |
| La | 11 ± 3 | 4 ±0 |
| Ce | 82 ± 15 | 68 ± 7 |
| Pr | 84 ± 6 | 107 ± 6 |
| Nd | 166 ± 27 | 128 ± 4 |
| Sm | 85 ± 13 | 67 ± 3 |
| Eu | 38 ± 4 | 31 ± 3 |
| Gd | 155 ± 14 | 127 ± 8 |
| Tb | 18 ± 3 | 15 ± 2 |
| Dy | 140 ± 26 | 120 ± 16 |
| Ho | 18 ± 5 | 17 ± 1 |
| Er | 45 ± 5 | 38 ± 2 |
| Tm | 4 ± 1 | 4 ± 1 |
| Yb | 32 ± 6 | 28 ± 2 |
| Lu | 8 ± 3 | 5 ± 1 |
| Sc | 39 ± 0 | 29 ± 0 |

Pozo, G. *et al. Water Research.* 2017

# Strategic importance of Metals and Rare Earths



# Targeted recovery of Metals from Acid Mine Drainage

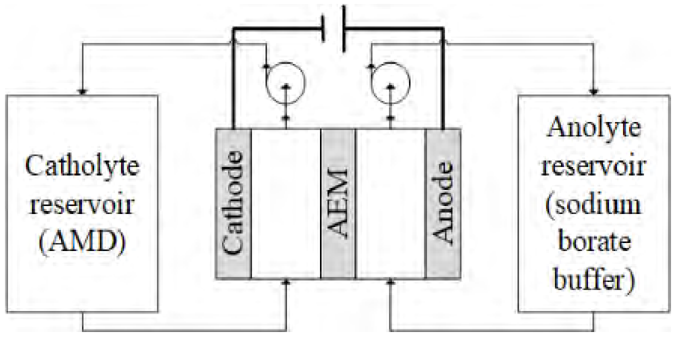



**Figure 1.** System diagram.

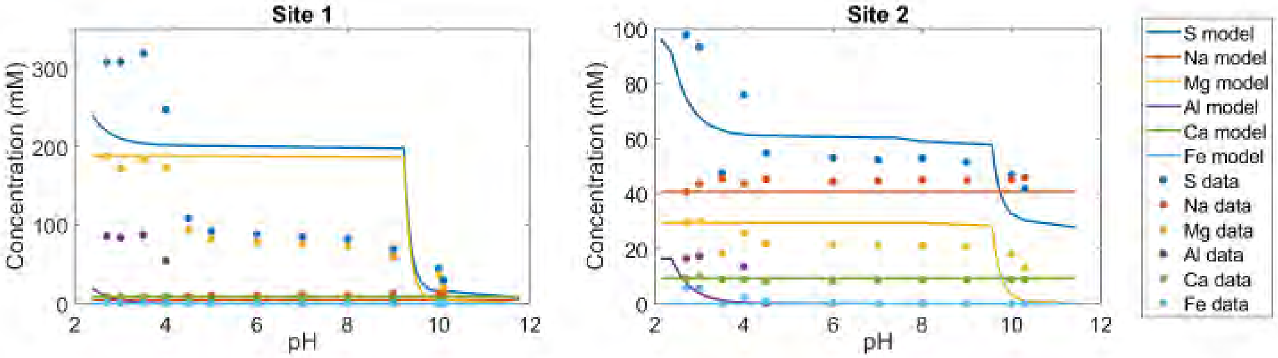



Figure 2: Experimental (markers) and modelled (lines) contaminants in the liquid phase during electrochemical treatment of acid mine drainage.

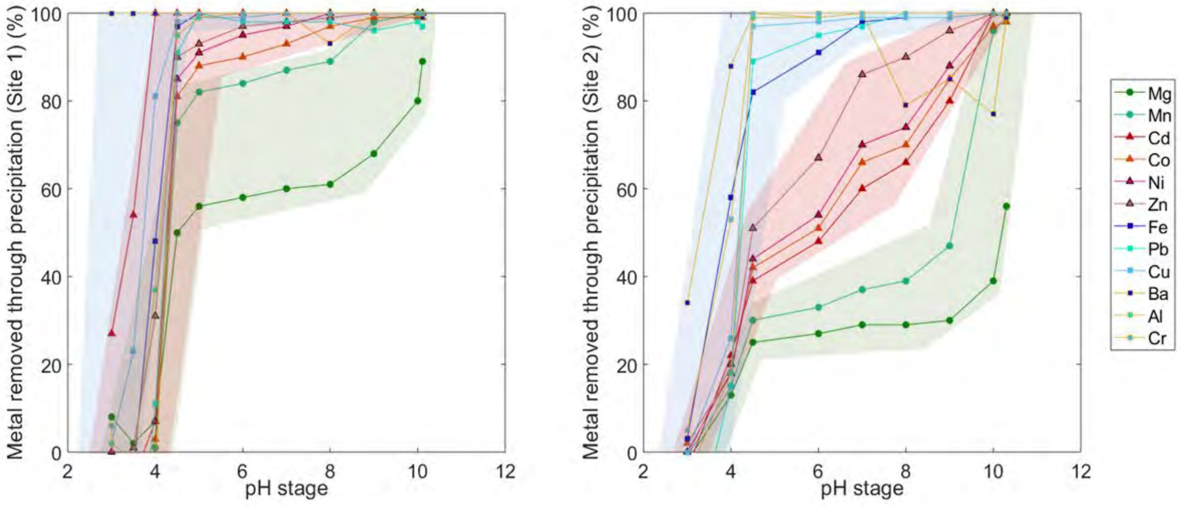



Figure 3: Percentage removal of metals from acid mine drainage through electrochemically induced precipitation. Pollutants removed at low pH are indicated by square markers (blue), those removed at high pH by circle markers (green) and those constantly removed by triangle markers (red). The three classes of results and not clearly seen in the Site 1 results due to the very high concentrations of SO42- and Mg, dominating the results (29 000 mg SO42- L-1, 4500 mg Mg L-1).

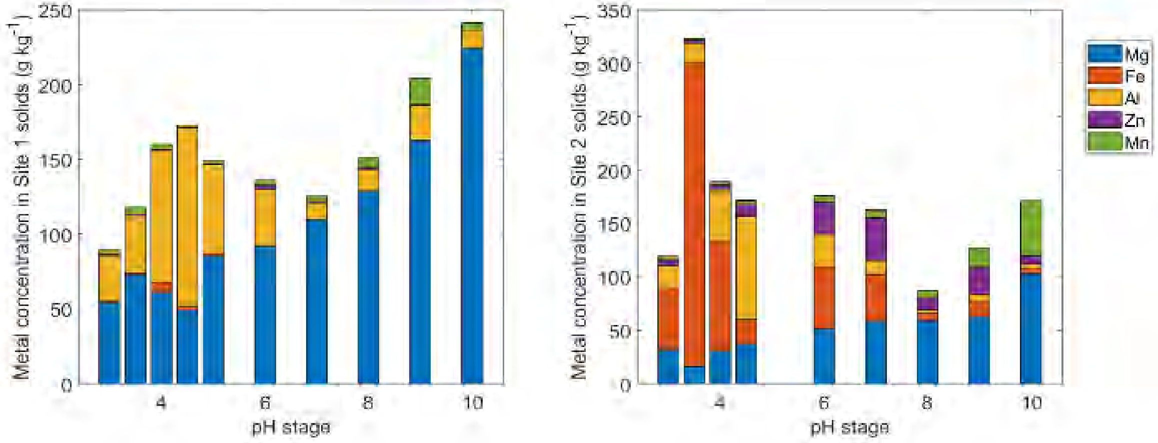
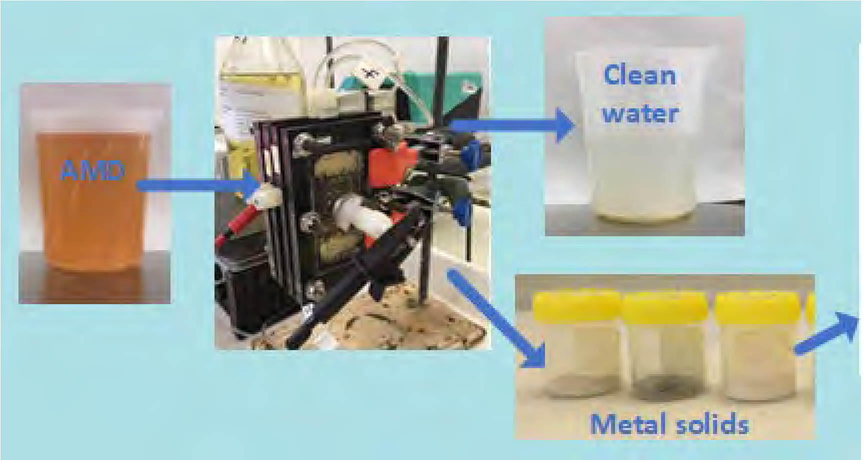
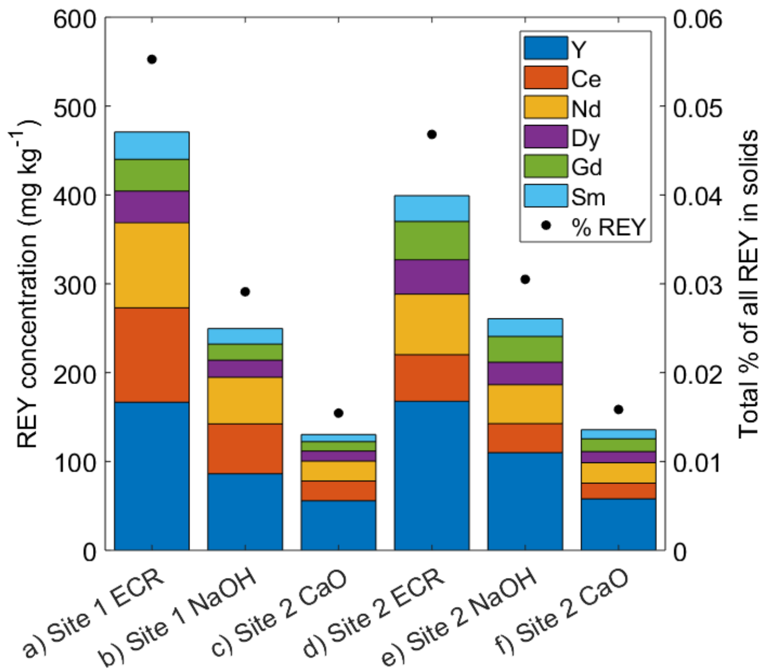



Figure 4: Solids composition of key major metals at increasing pH stages. Left: results from the treatment of AMD from Site 1. Right: results from the treatment of AMD from Site 2

Thompson-Brewster. *et al. Energy Environ. Sci.* under review

# Targeted recovery of Rare Earth Elements



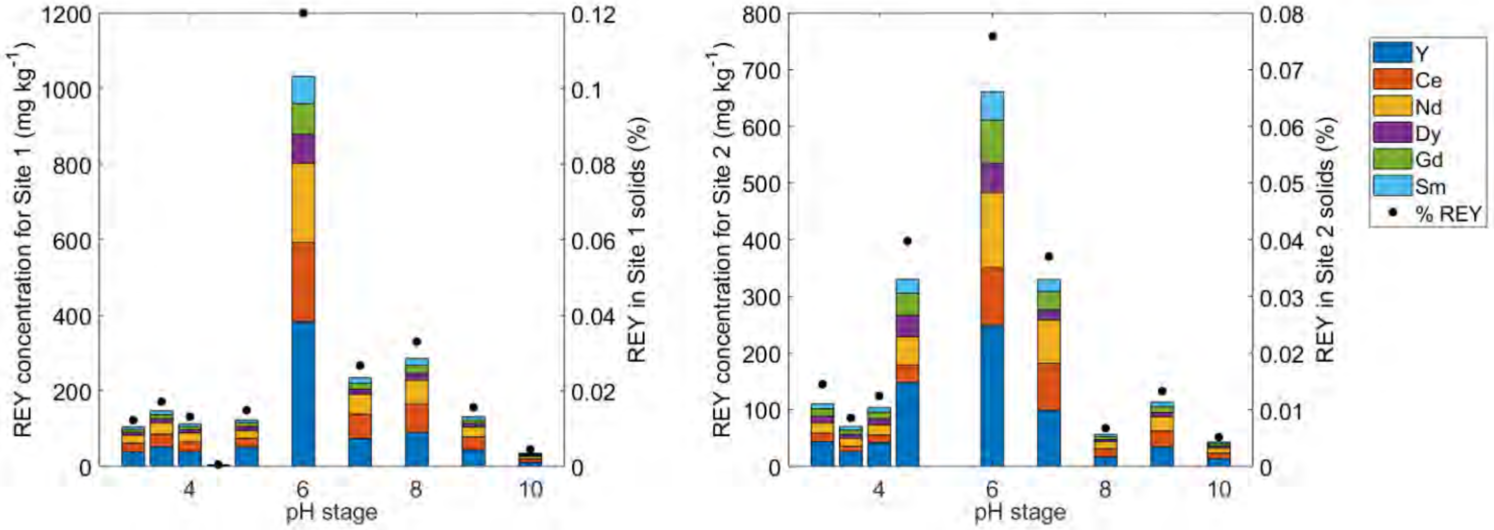




Figure 5: Solids composition of rare earth element oxides at varying pH stages. The gap between the presented REYs and the total percentage is comprised of Erbium (Er), Europium (Eu), Holmium (Ho), Lutetium (Lu), Praseodymium (Pr), Terbium (Tb), Thulium (Tm) and Ytterbium (Yb). Left: results from the treatment of AMD from Site 1. Right: results from the treatment of AMD from Site 2.

Thompson-Brewster. *et al. Energy Environ. Sci.* under review

# A novel approach to electrochemical treatment of AMD

**A novel hybrid process for treatment of AMD + Recovery of sulfuric acid**

**+ Recovery of metals**

- Estimated cost: \$80 $m^{-3}$ to meet creek discharge standards (high CAPEX/low OPEX; 10 year estimated lifetime) – 20% cheaper than current technologies

+ Recovery of sulfuric acid (market value is~ \$80-120 $ton^{-1}$ delivered to site)

+ Recovery of trace metals as nutrients for next-generation fertilisers (Zn, Al, Mg, Mn)

+ Recovery of Rare Earth Elements with exciting applications & commercial value:

Gadolinium oxide: \$19,025.16 USD $ton^{-1}$

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# Thank you

Dr Pablo Ledezma

p.ledezma@awmc.uq.edu.au

Dr Emma Thompson-Brewster

Prof. Jurg Keller

Dr Guillermo Pozo

(soon) Dr Enric Blazquez

KINETIC GROUP WORLDWIDE

Australian Government

Australian Research Council

Advanced Water Management Centre

Research Group on Biological Treatment and Valorisation of Liquid and Gas Effluents GENOCOV

**SULFRED DP 120104415.– A novel bioelectrochemical system for wastewater sulfate reduction**

# AMD properties before and after treatment with Electrochemical Reactor, NaOH and Lime dosing

| | Site 1 | | | | Site 2 | | | | ANZECC 2000 guidelines | |
|---|---|---|---|---|---|---|---|---|---|---|
| Element (mg $L^{-1}$) | Original | ECR | NaOH | Lime | Original | ECR | NaOH | Lime | Stock water* | Recreational purposes** |
| Al | 2317 | 0.6 | 0.03 | 0.7 | 443 | 0.6 | 0.3 | 5.1 | 5 | 0.2 |
| B | 0 | 2.7*** | 0 | 0 | 0.7 | 0.8 | 0.6 | 0.6 | 5 | 1 |
| Cd | 0.1 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0.01 | 0.005 |
| Ca | 364 | 234 | 354 | 442 | 368 | 367 | 377 | 489 | 1000 | Not listed |
| Cr | 0.02 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 1 | 0.05 |
| Co | 5.2 | 0 | 0.01 | 0.06 | 3 | 0.01 | 0.05 | 0.02 | 1 | Not listed |
| Cu | 65 | 0.03 | 0.05 | 0.07 | 9 | 0.2 | 0.5 | 0.4 | 0.4 | 1 |
| Fe | 66 | 0 | 0 | 0 | 324 | 0.3 | 0 | 0.09 | Not sufficiently toxic | 0.3 |
| Pb | 6.2 | 0.1 | 0.07 | 0.1 | 1.3 | 0.01 | 0.06 | 0.05 | 0.1 | 0.05 |
| Mg | 4564 | 1022 | 2148 | 1188 | 715 | 318 | 245 | 7.4 | 2000 | Not listed |
| Mn | 245 | 0.8 | 0.2 | 0.2 | 63.4 | 0.9 | 0.7 | 0.1 | Not sufficiently toxic | 0.1 |
| Ni | 2.1 | 0 | 0 | 0 | 4.7 | 0.01 | 0 | 0 | 1 | 0.1 |
| Zn | 55 | 0 | 0 | 0 | 106 | 0.3 | 0.03 | 0.1 | 20 | 5 |
| $SO_4$-S | 29 547 | 4962 | 27 938 | 5769 | 9391 | 4195 | 8597 | 3099 | 1000 | 400 |

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# Prediction of long-term salt generation from coal spoils

Mansour Edraki, Neil McIntyre, Thomas Baumgartl and Melinda Hilton

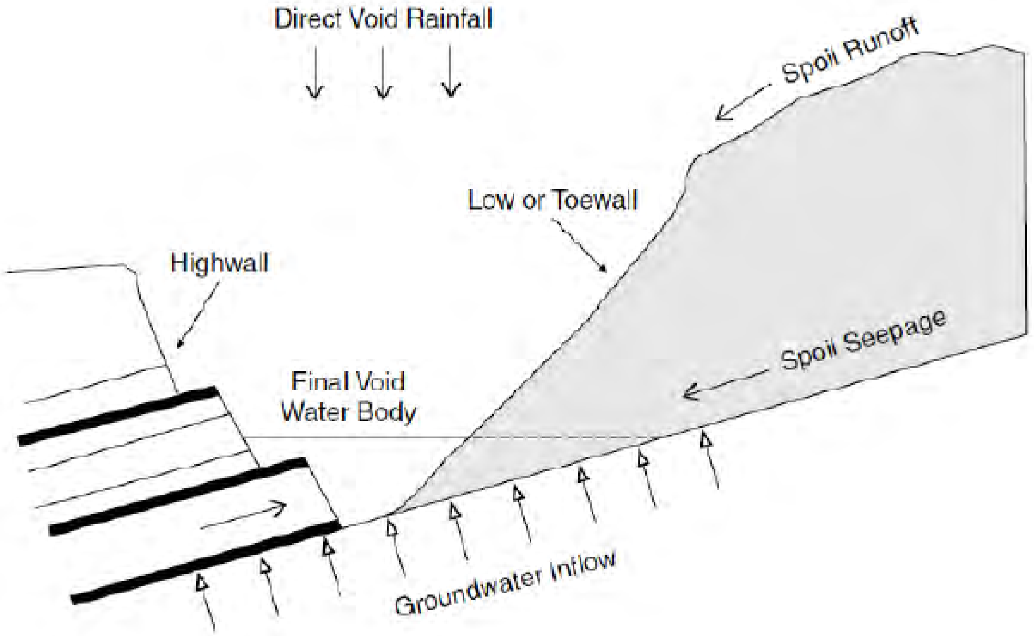
# Background

Final void salinity

Spoil salts

$$Vs = \frac{Gw_s + Rc_s + Gs_s}{Gw + Rc + Gs + Cr_o - E}$$

groundwater rainfall spoil runoff




Hancock, G., Wright, A., De Silva, H. (2005). Long-term final void salinity prediction for a post-mining landscape in the Hunter Valley, New South Wales, Australia, Hydrological processes 19(2): 387-401.

# Aim

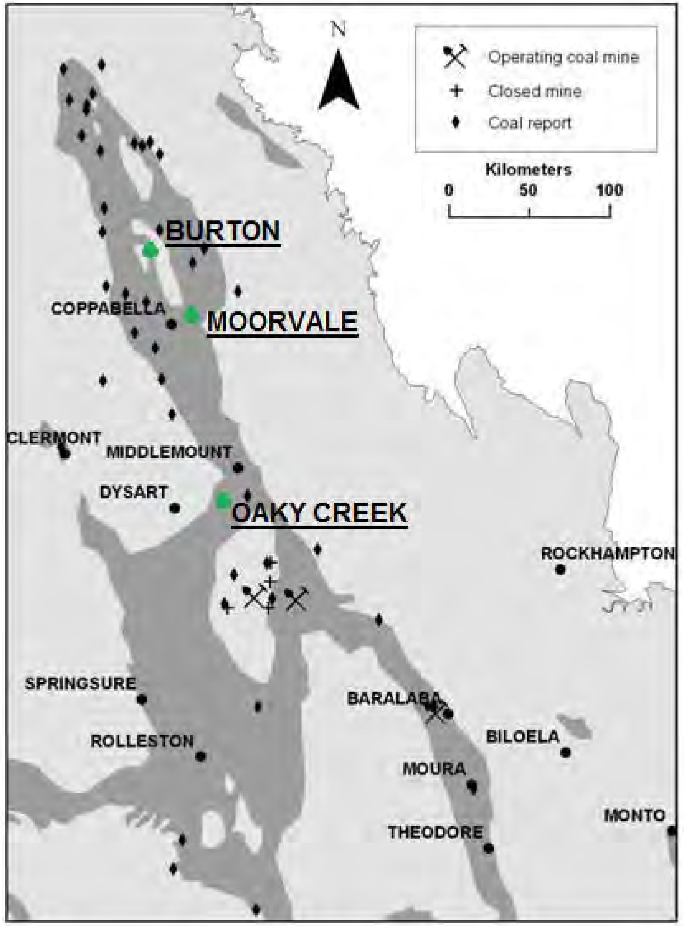
To develop a process for estimating long-term salinity generation rates from different classes of mine spoil and spoil pile configurations that can be used in conjunction with water balance models to predict long-term final void salinity levels or the residual risk to receiving surface water or groundwater environments.

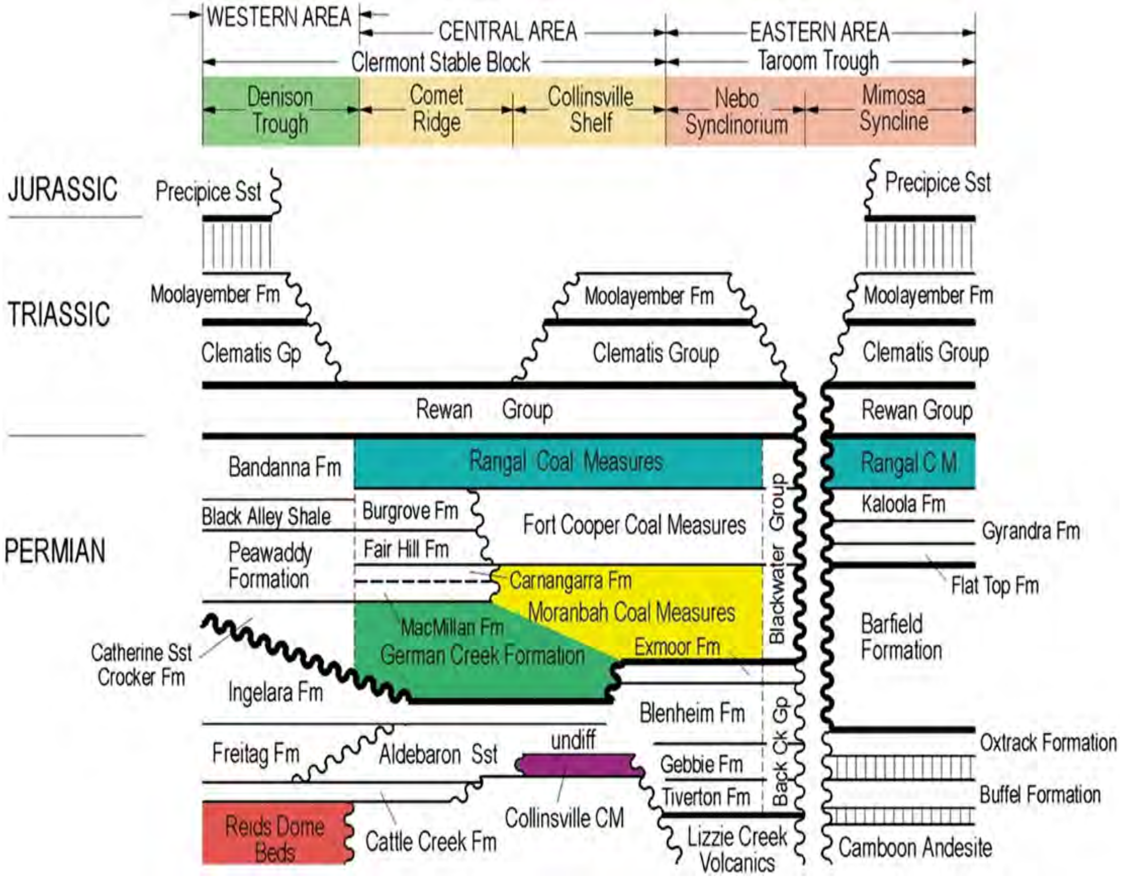
# Field observations





# Target geology

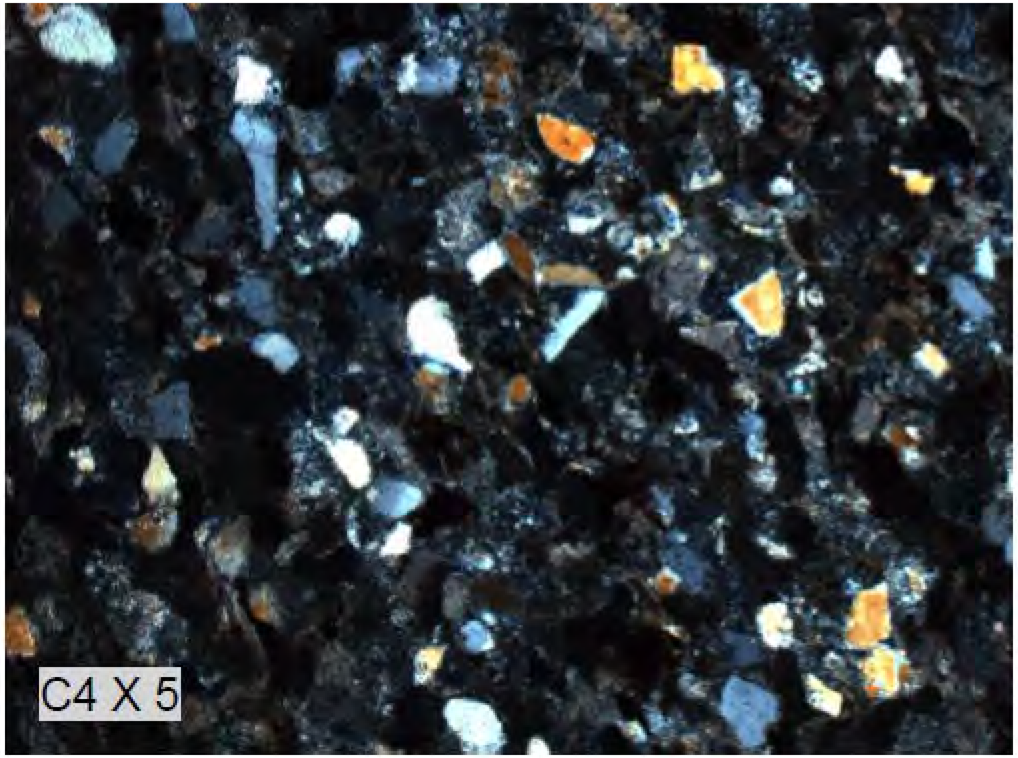


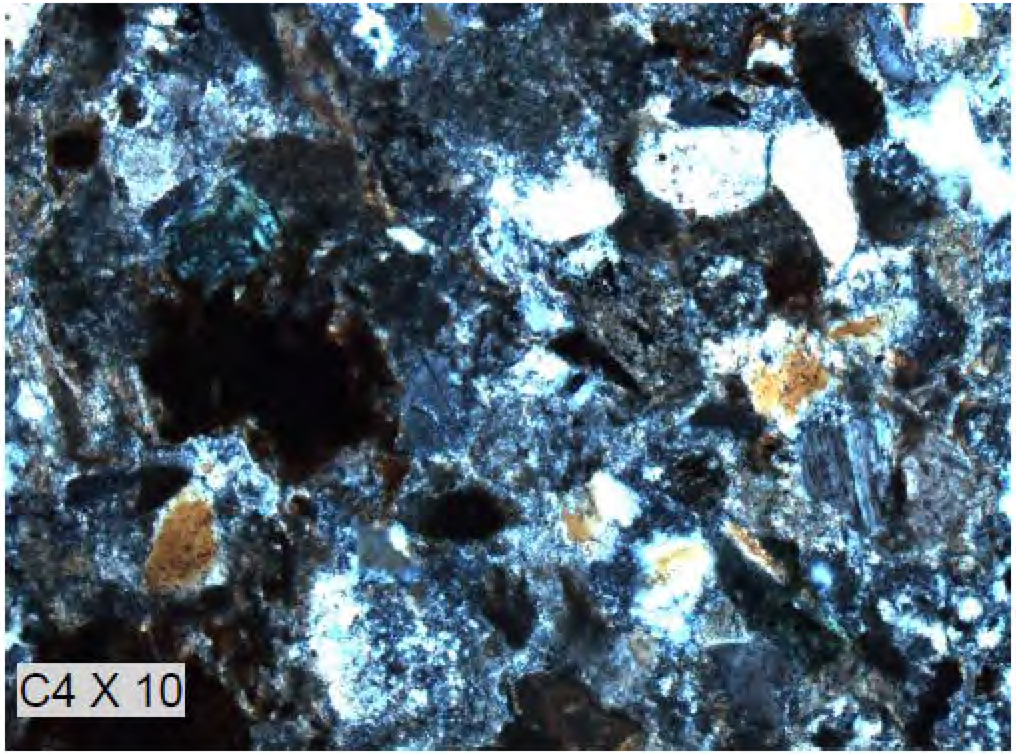



# Sampling


Burton:
A2
A3
A4
A5
A6
A7
A8
A10
A11
A12
Moorvale:
B1
B2
B3
B4
B5
B6
B7
B8
B9
Oaky Creek:
C2
C3
C4
C5
C6
C7
15cm

# Initial classification



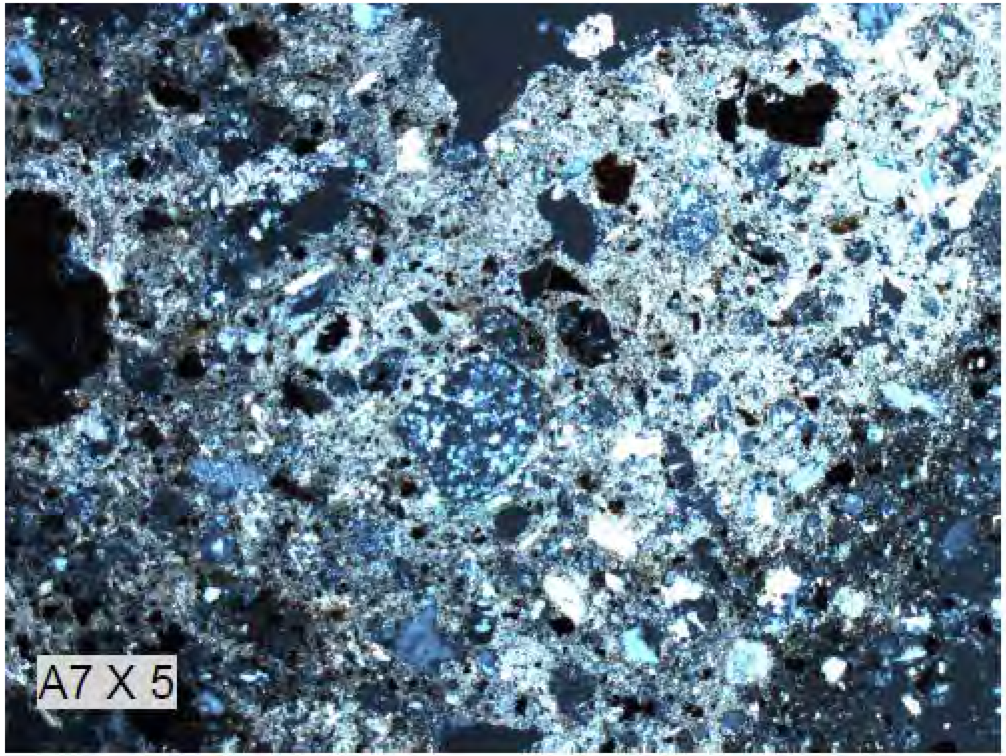




500$\mu$m

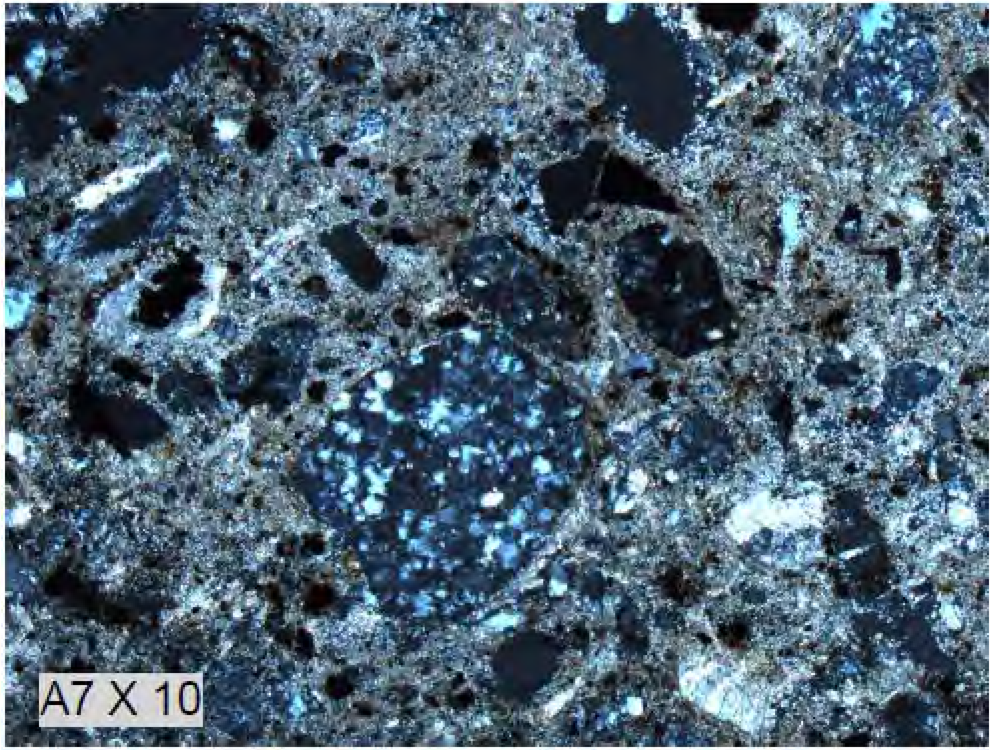
250$\mu$m

1) medium to coarse grained sandstones with a grain-supported texture

# Initial classification



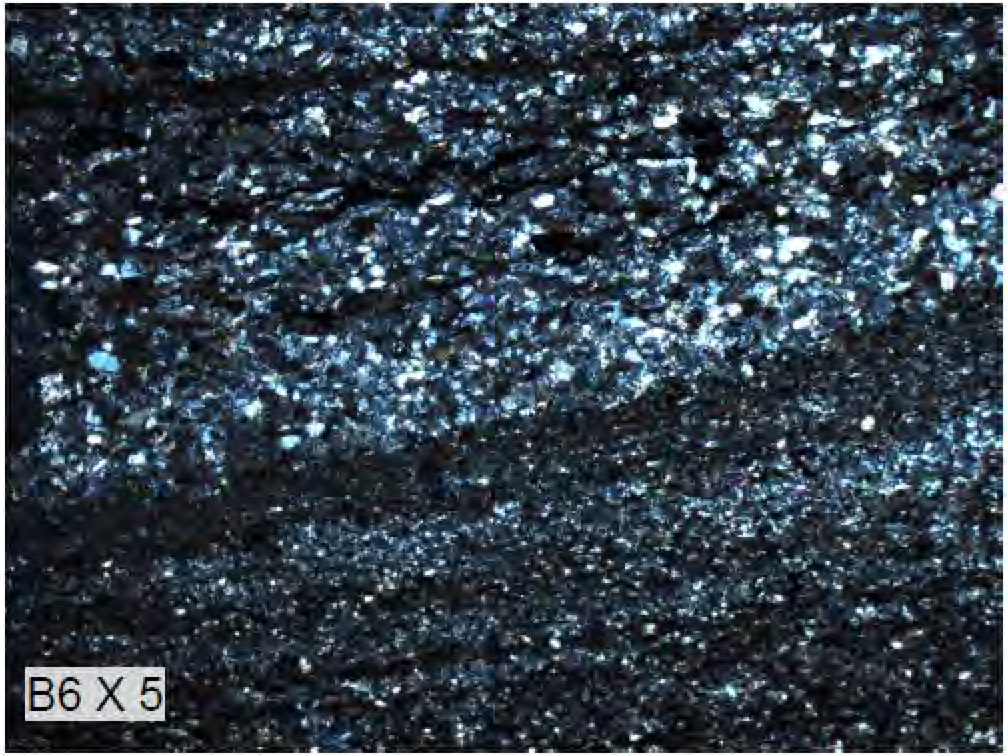

500µm

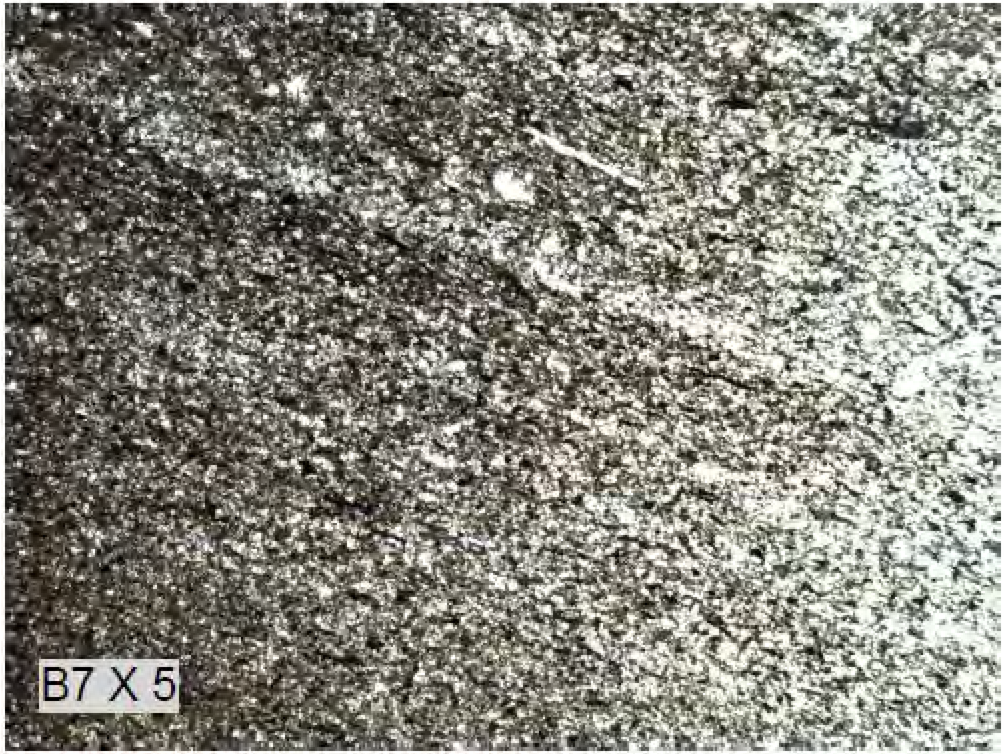



250µm

2) fine- to medium- grained sandstones with abundant authigenic minerals

# Initial classification



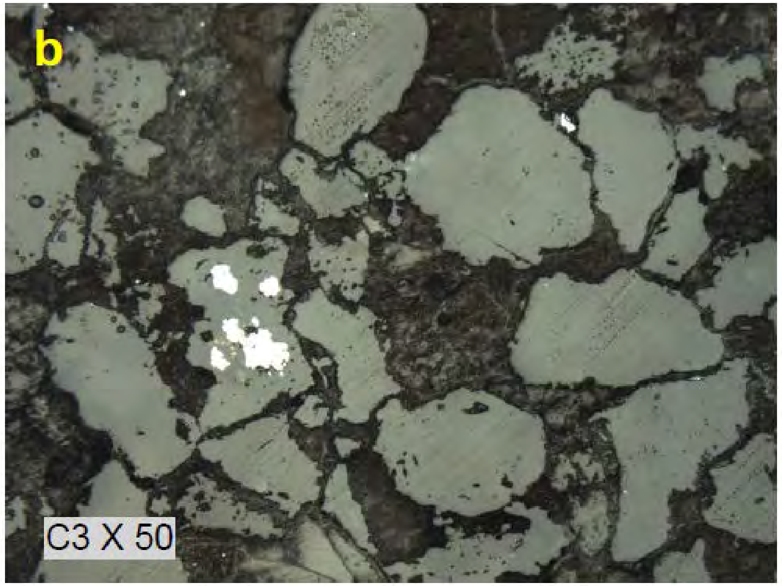



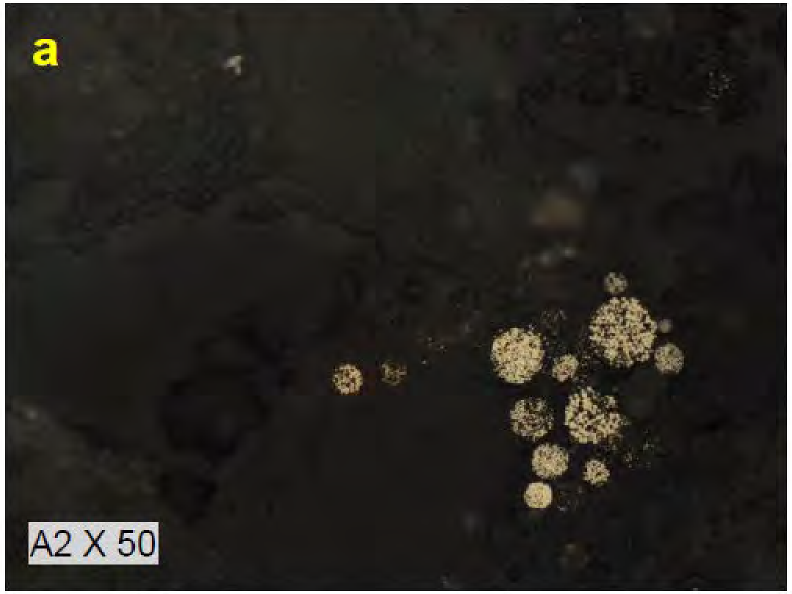

500µm

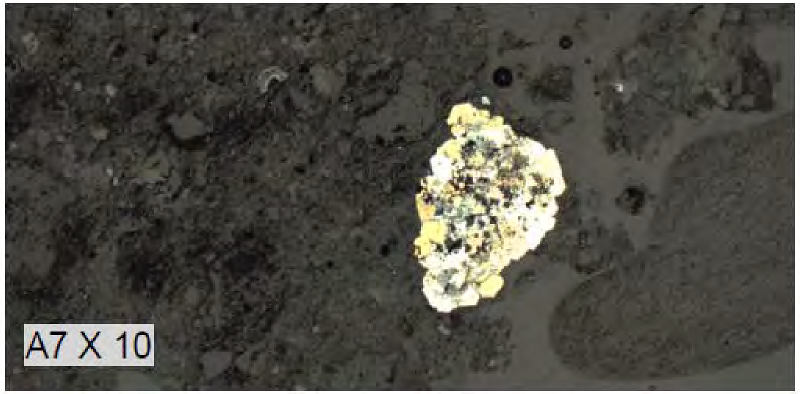
250µm

3) mudrocks consisting of siltstone and mudstone

# Initial classification

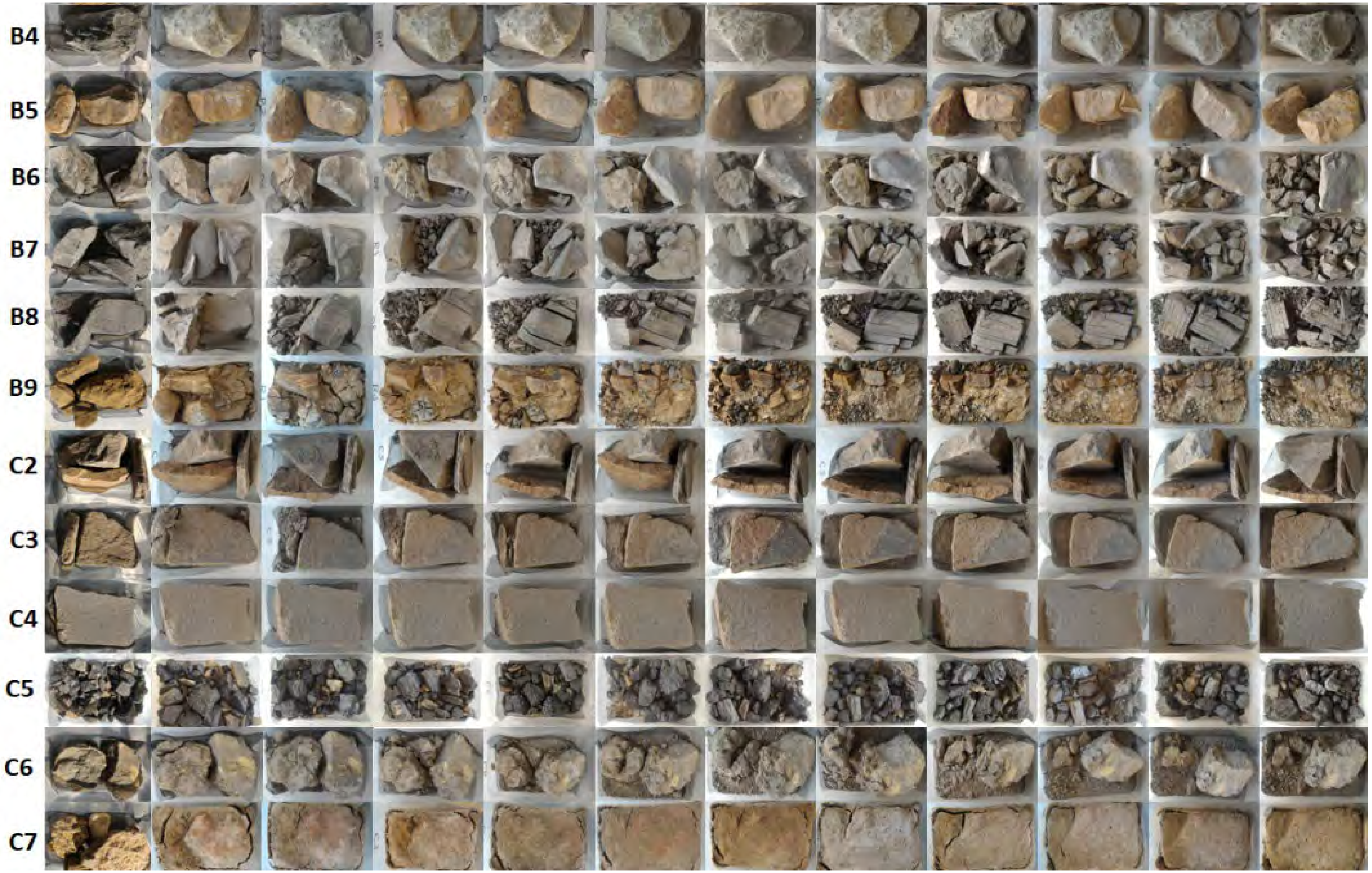


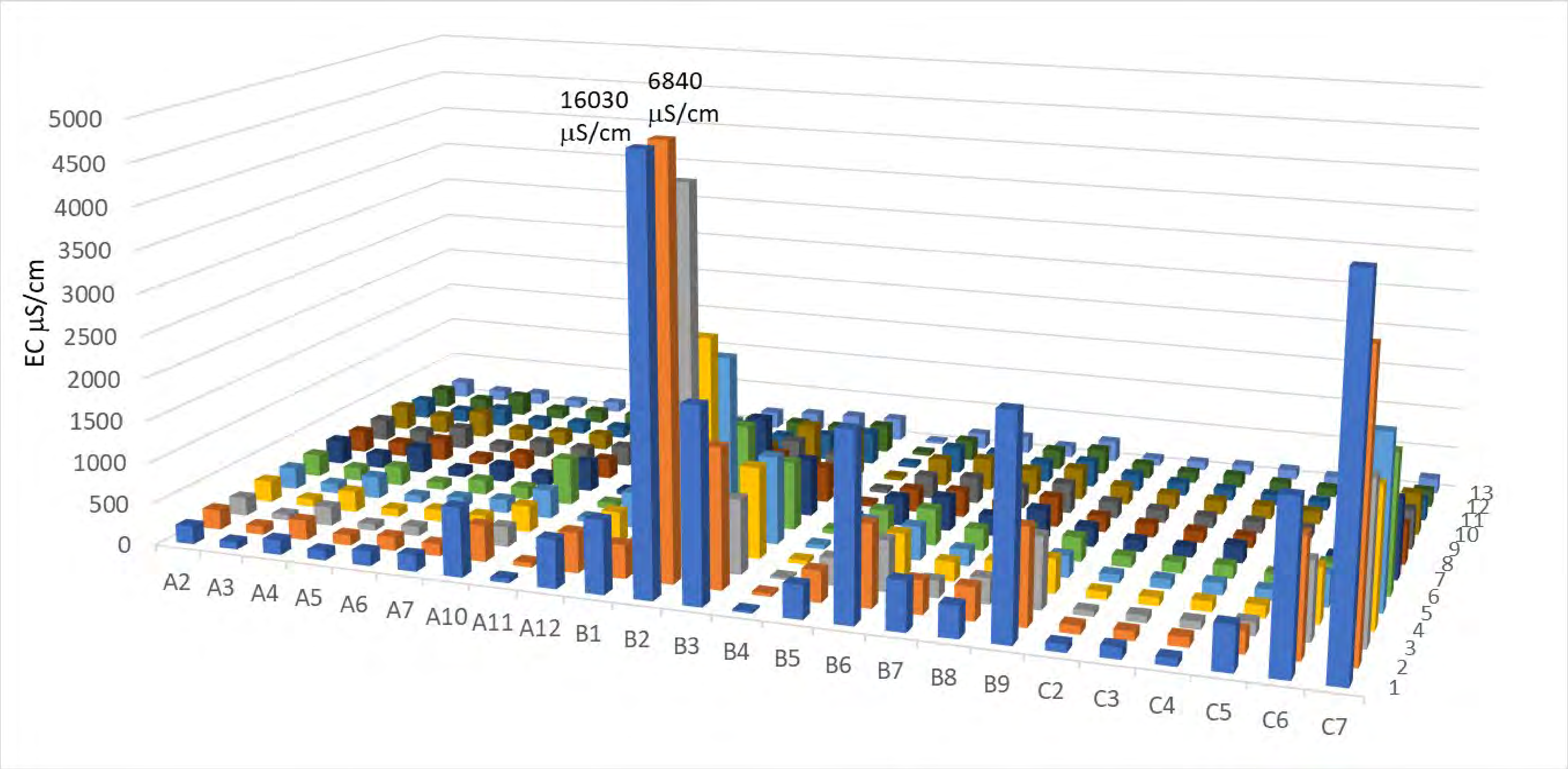



# Degradation tests results

# Degradation tests results



# Degradation tests results



# Salt release response of spoil to varying moisture conditions – small scale laboratory tests (Buchner Funnel Experiments)


A10 <2mm

A10 2-6mm

A10 >6mm

B8 <2mm

B8 2-6mm

B8 >6mm

B9 <2mm

B9 2-6mm

B9 >6mm

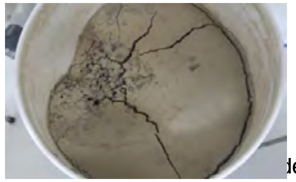
C4 <2mm

C4 2-6mm

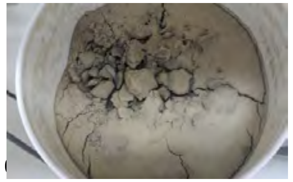
C4 >6mm

C6 <2mm

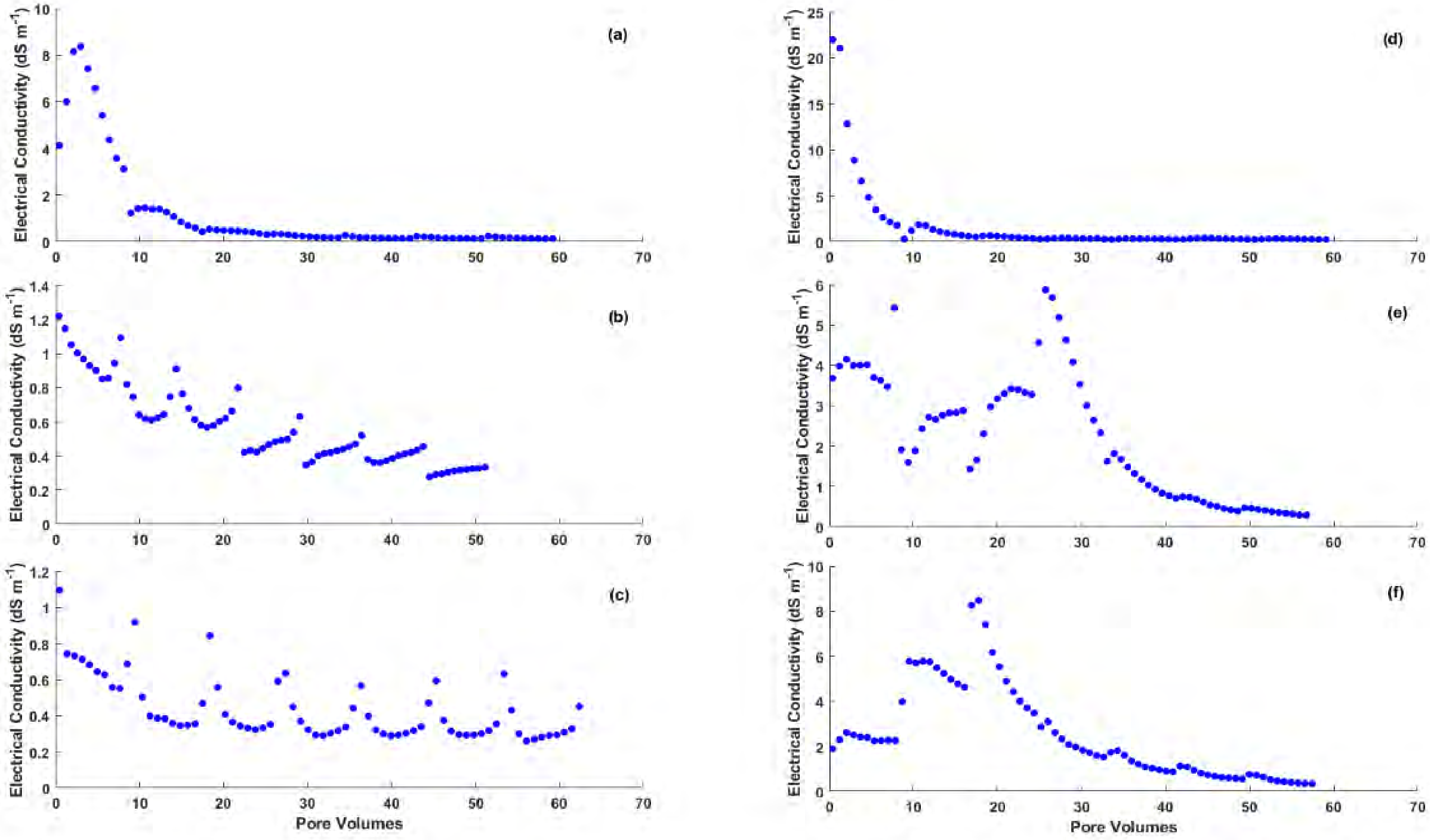
C6 2-6mm



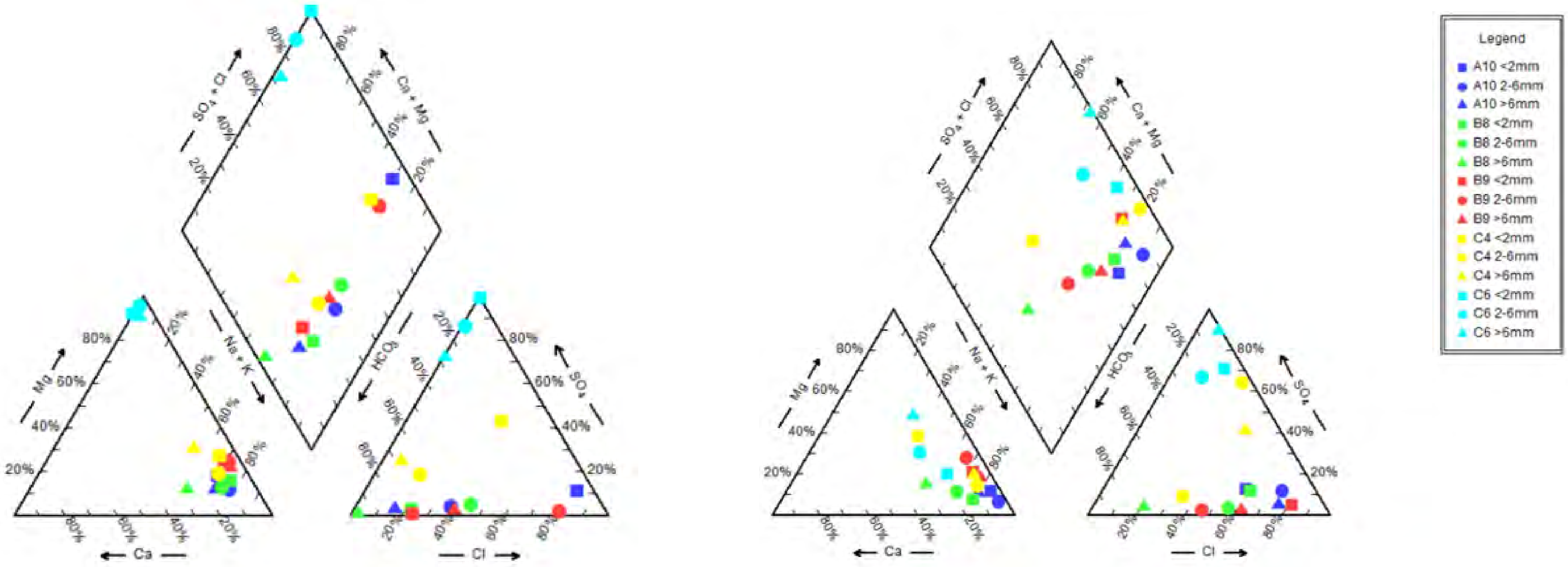
C6 >6mm



# Salt release rates- example of decay curves



# Leachate chemistry



# Spoil classification

The spoil samples were further classified into seven classes with respect to the degree of potential salt release using results of ‘first flush’ and ‘degradation’ tests:

1. Rock-like, competent Permian sandstones with intact initial rock fabric. These spoils do not show signs of degradation but can potentially produce salinity in the long term.
2. Rock-like, relatively fresh Permian sandstones (± siltstone) with authigenic minerals particularly carbonates and white mica. This group may contribute to salinity depending on the degree of pre-mining geological weathering and alteration (mineral replacements).
3. Soil-like, weathered Permian sandstones (± siltstone) which will produce salt.
4. Soil-like, weathered Tertiary and Quaternary spoils. They can produce significant amounts of salts.
5. Coal rejects that would produce salinity (mainly sulfate) depending on the pyrite content.
6. Soil-like or rock-like Permian (Rangal) fine-grained mudrocks, which are often weathered, and degrade and produce salts.
7. High sulfur Lower Permian spoils with signs of AMD. These are potentially dispersive sandstones, with pyrite content, abundant inert minerals and low neutralising capacity.

# Spoil pile configuration

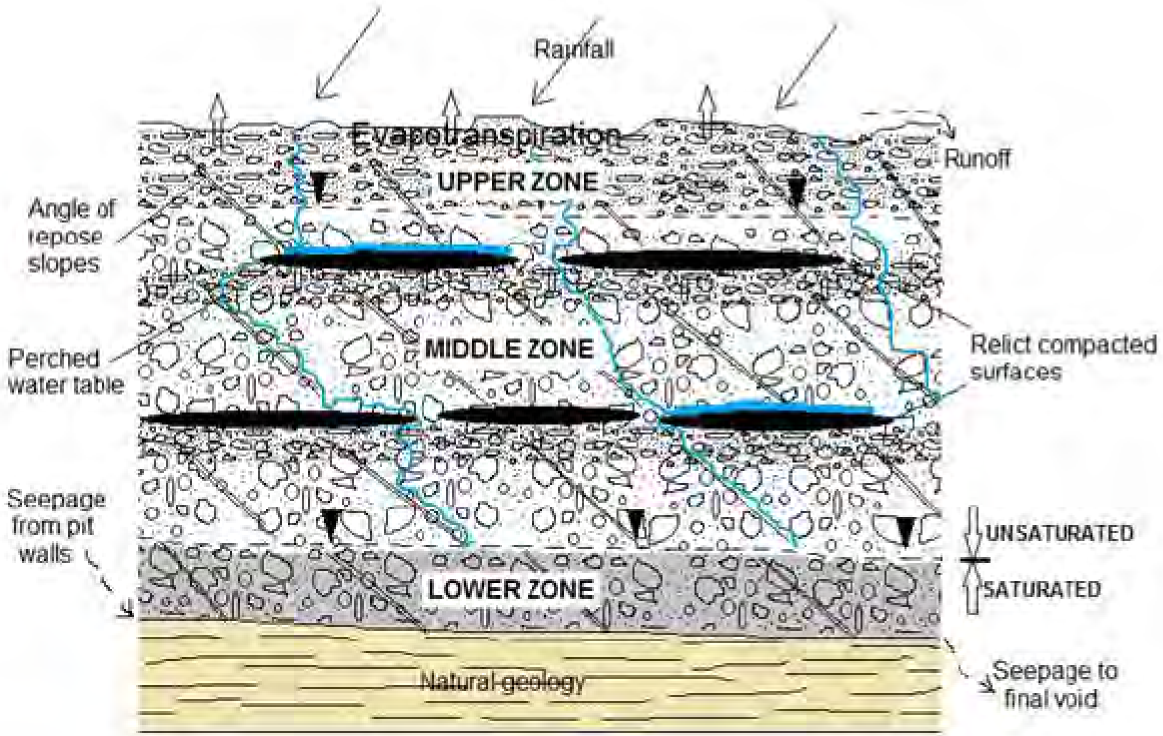



*Figure 54 Spoil seepage processes modified from the conceptual model of Simmons et al. (2015)*

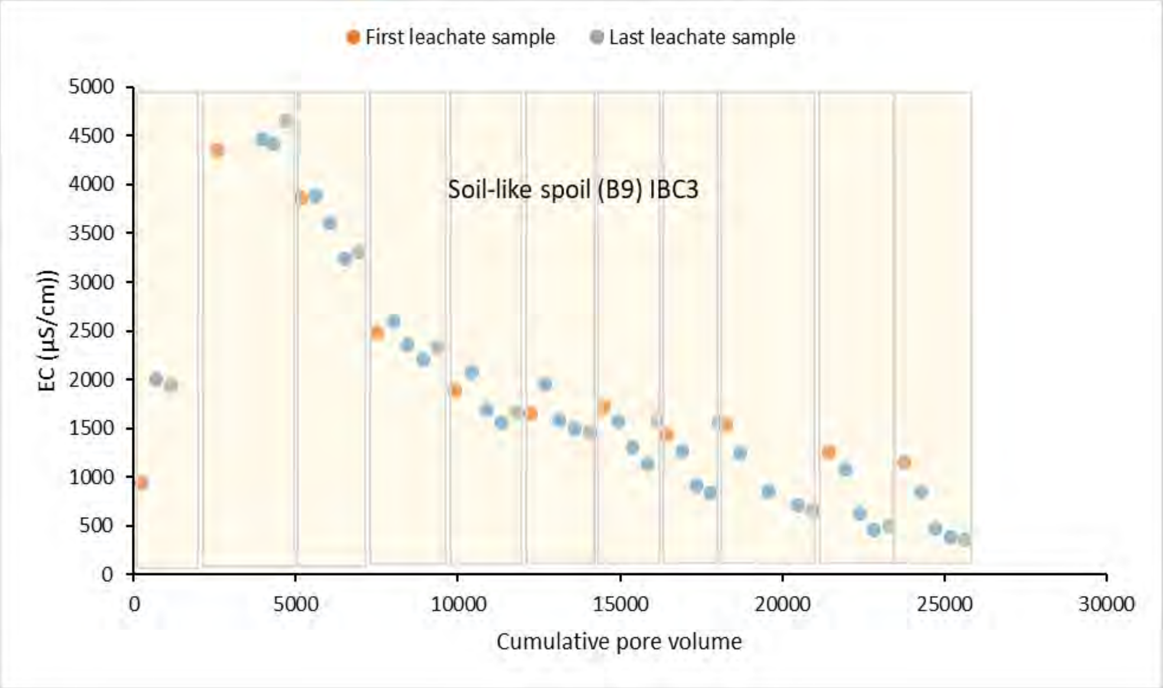
# Sampling in IBCs

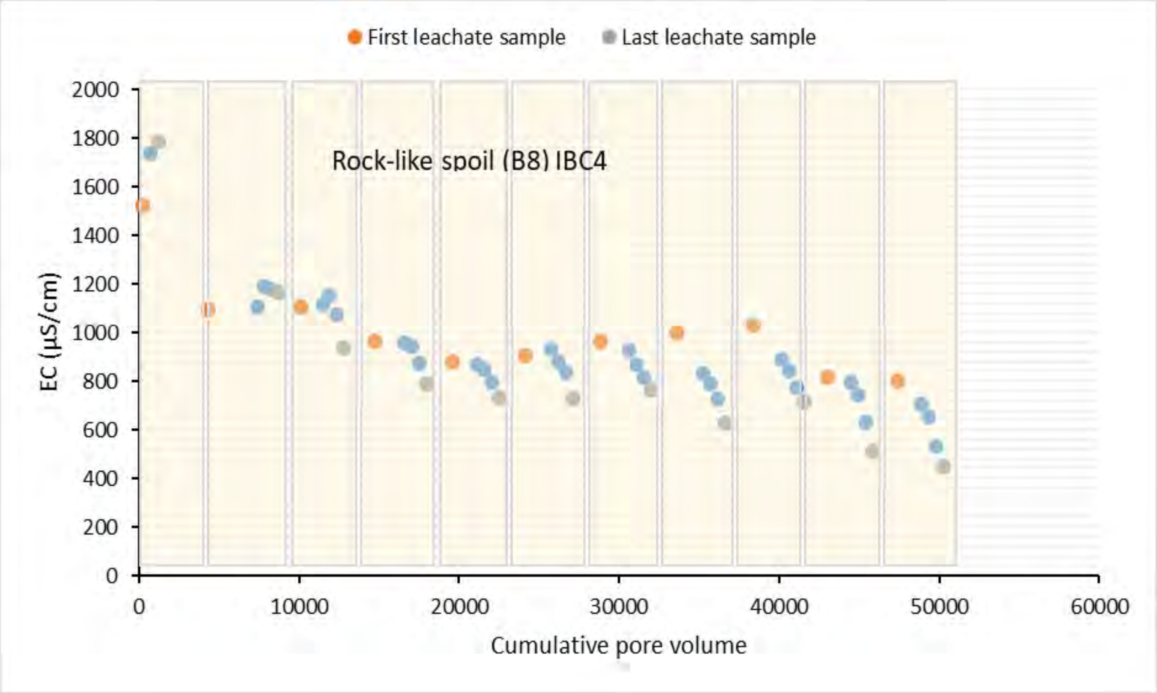

# Leaching chemistry and hydrology at meso-scale (mesocosm experiments)

Soil-like sample

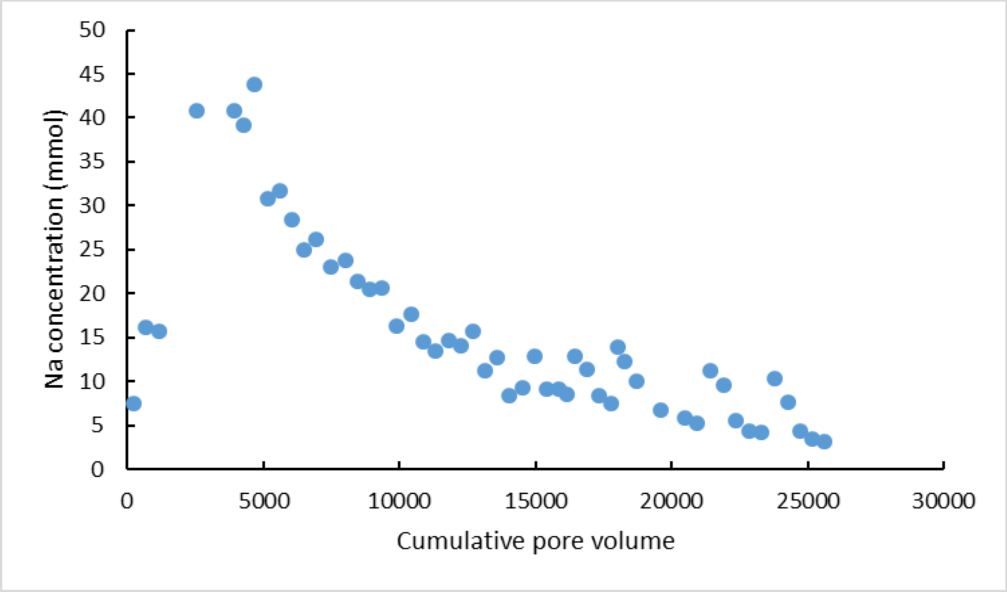
Rock-like sample

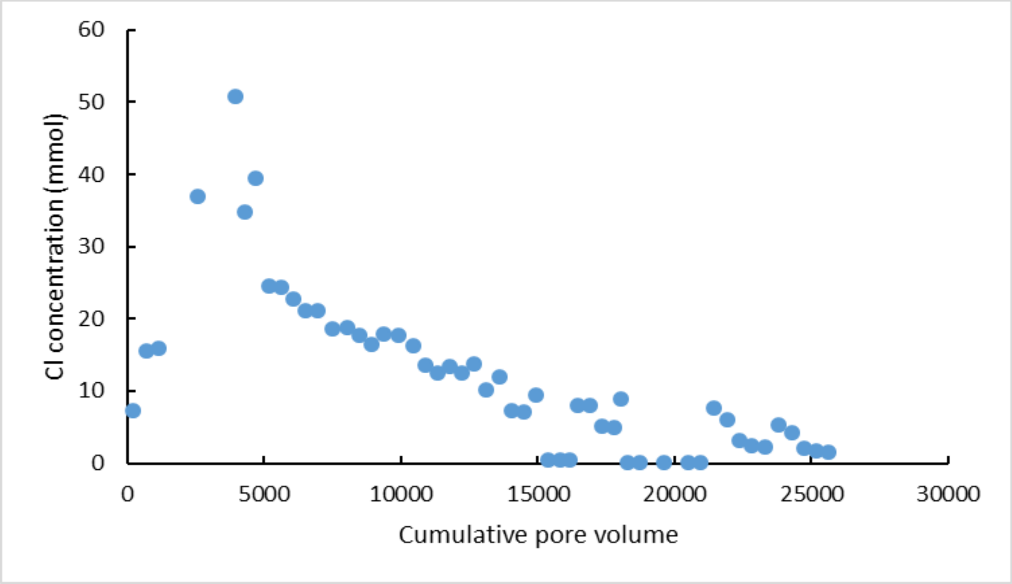
# Leaching chemistry and hydrology at meso-scale (mesocosm experiments)



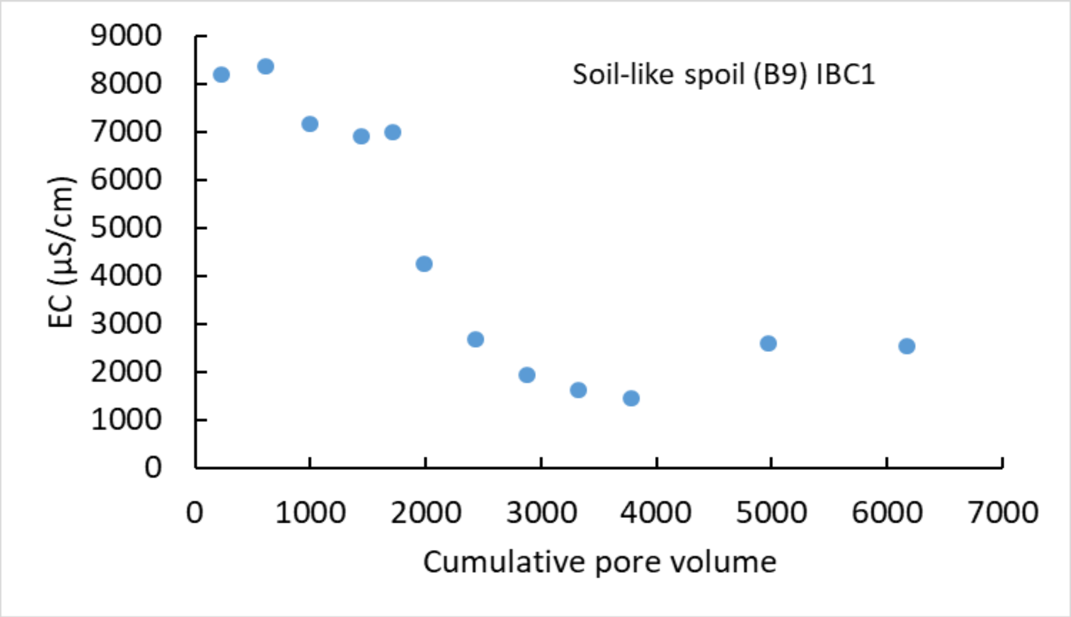



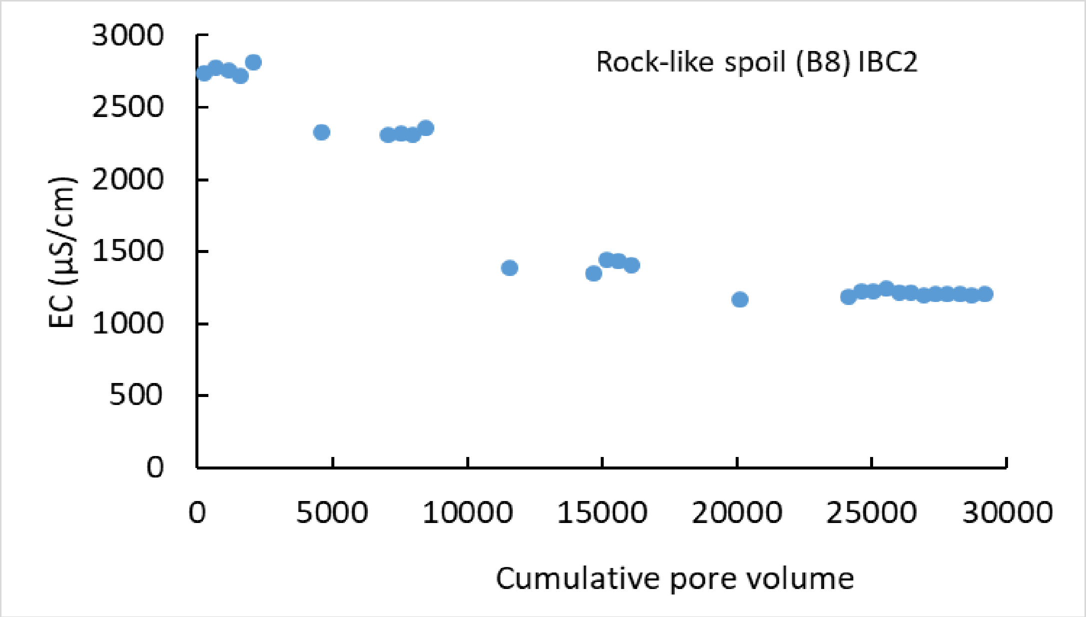
# Leaching chemistry and hydrology at meso-scale (mesocosm experiments)



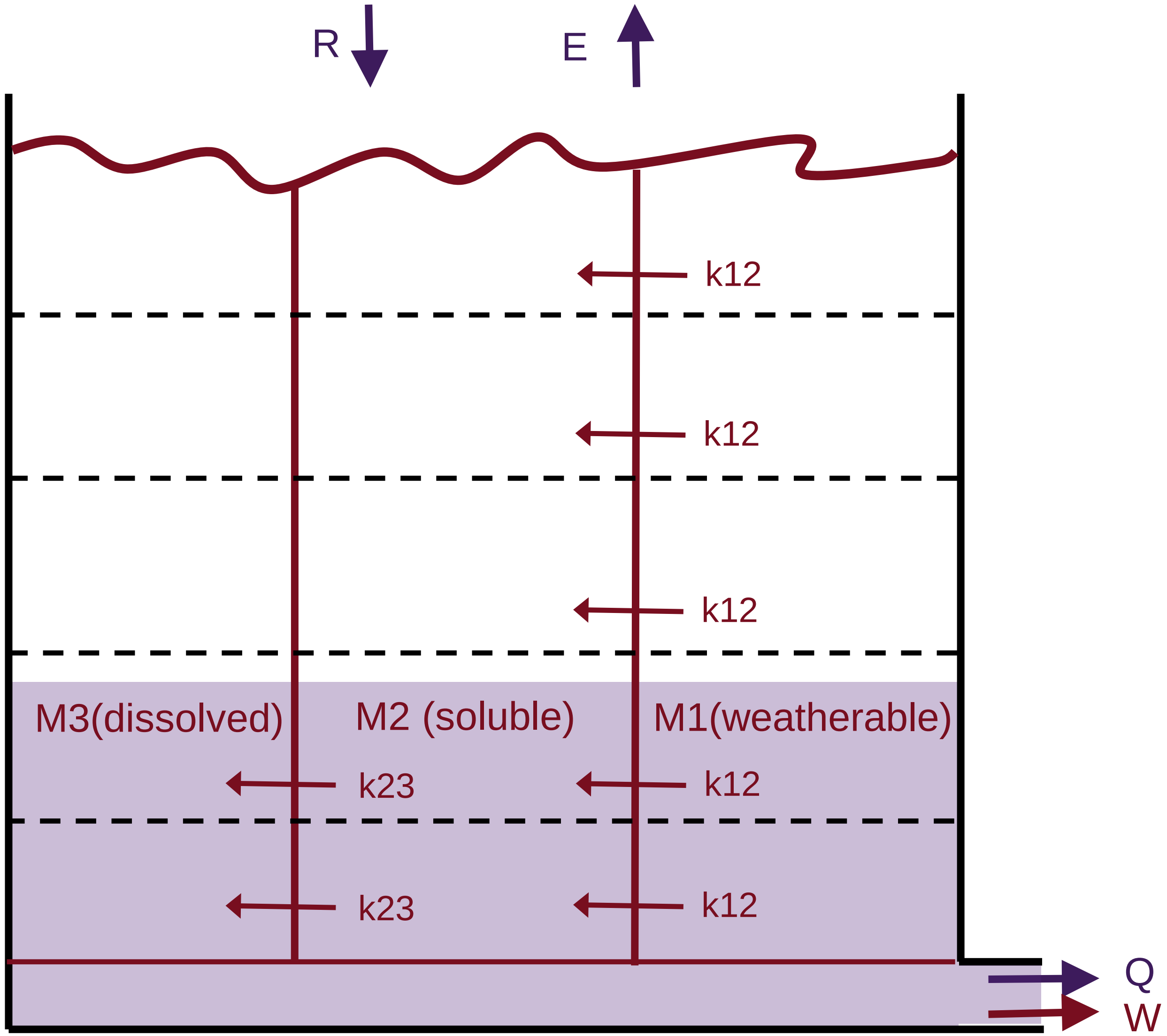



# Leaching chemistry and hydrology at meso-scale (mesocosm experiments)

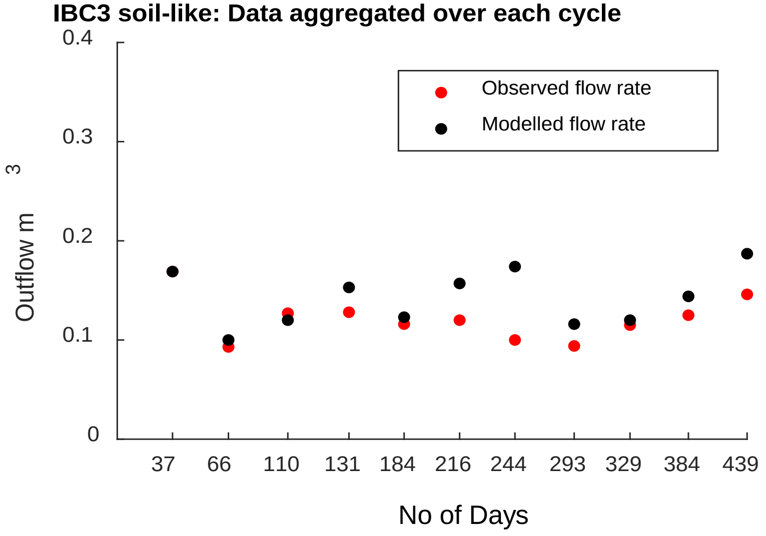


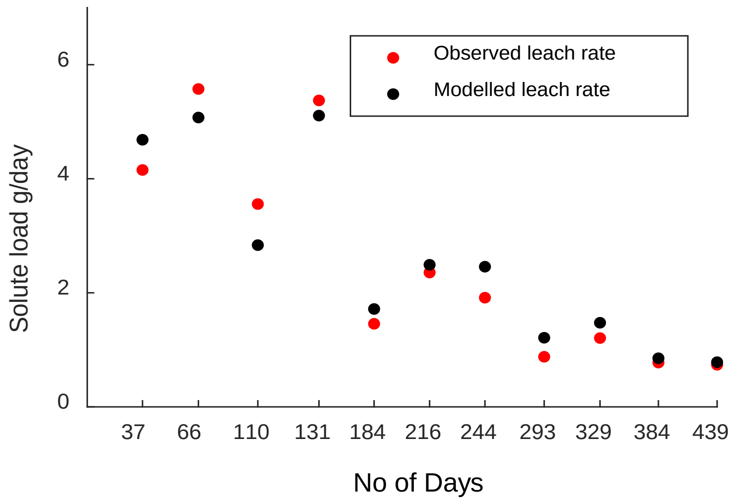



# Long-term prediction of salt generation from coal mine spoils

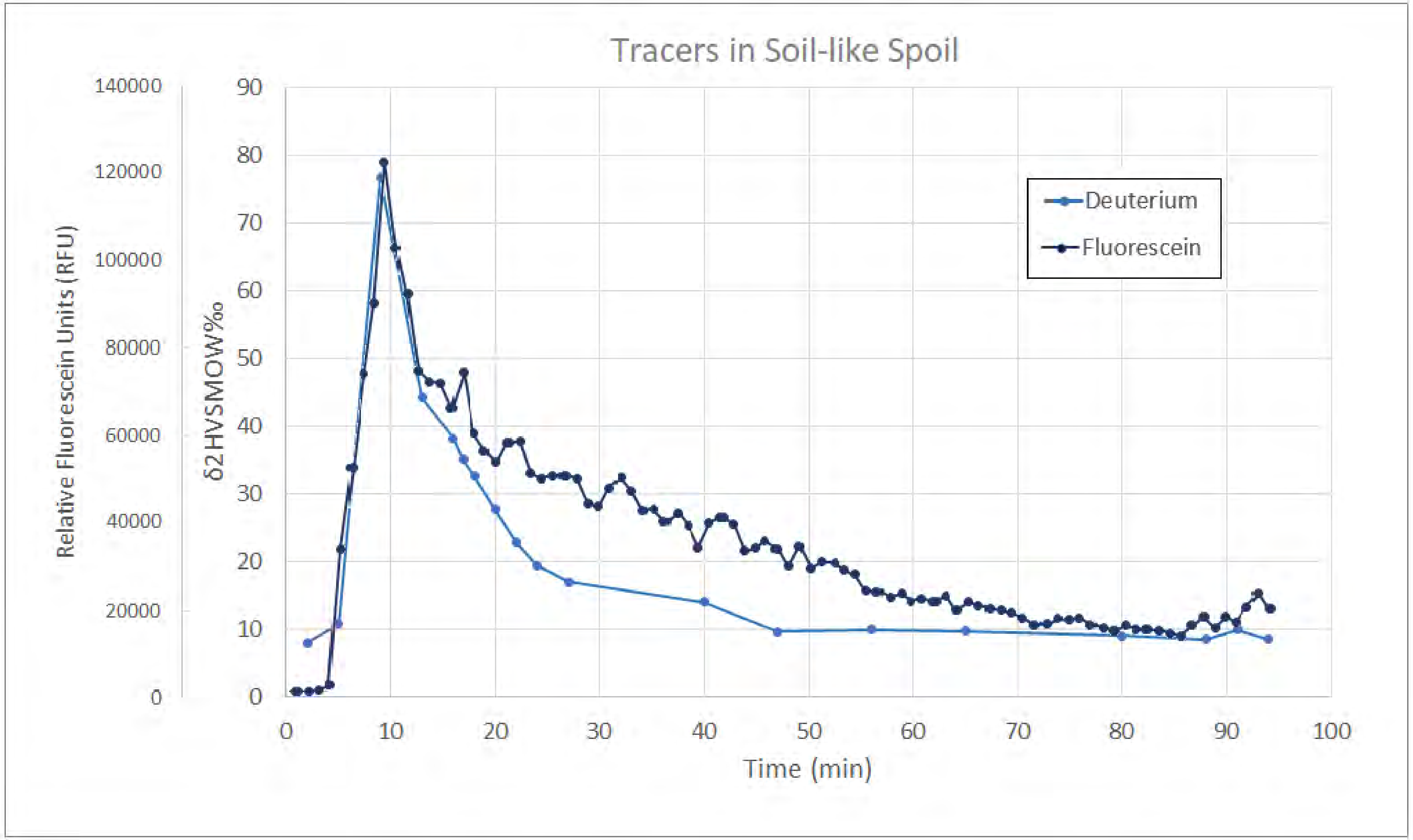


# Long-term prediction of salt generation from coal mine spoils

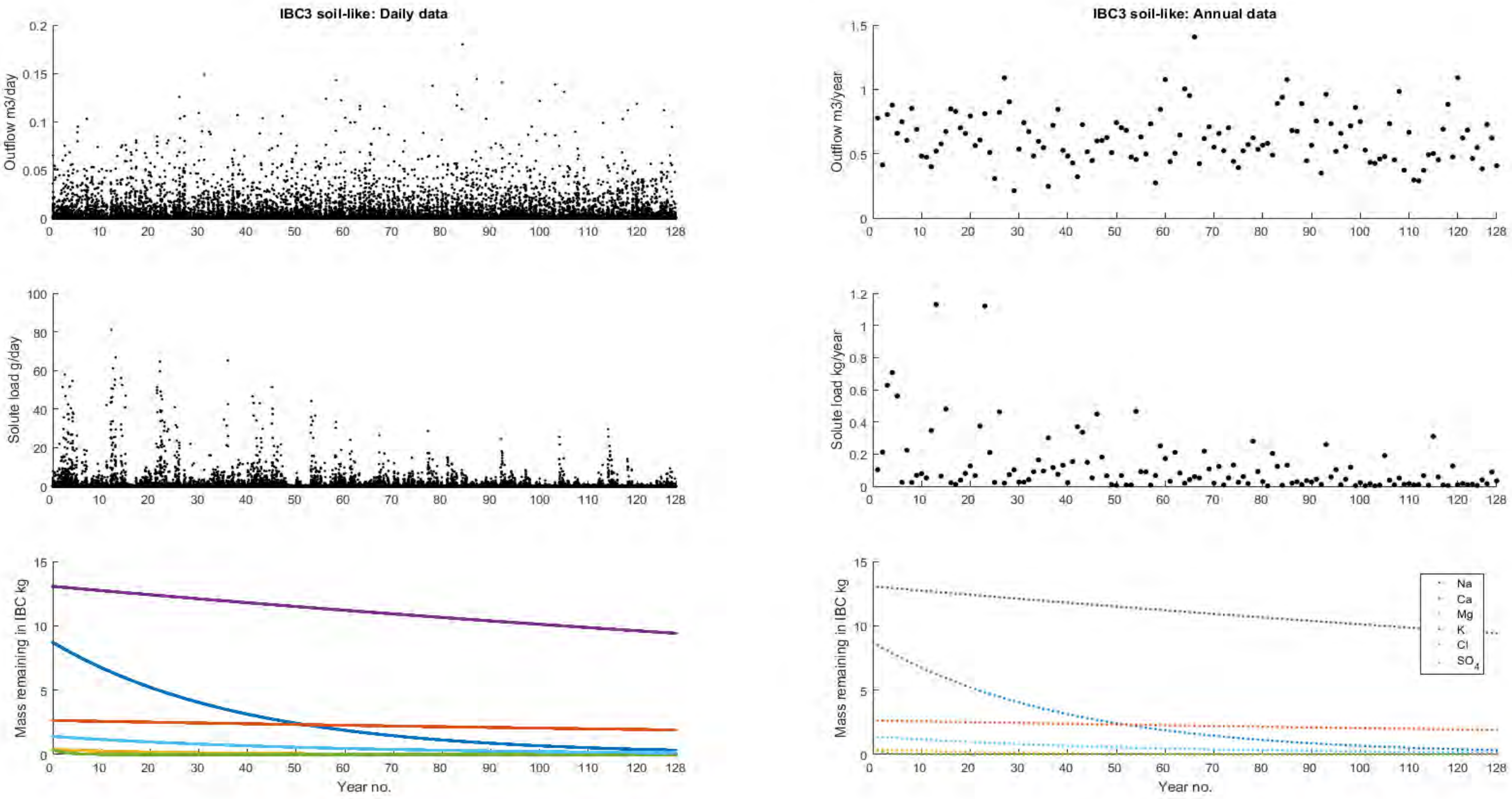


# Tracer test results



# Long-term prediction of salt generation from coal mine spoils



# Further work

Target new sites for spoil samples with reasons

Expansion of IBC experiments – how many new IBCs, which will be decommissioned

Refinement of IBC experiments – weighing scales, hydrologic monitoring, use of sprinkler

Refinement of lab experiments – moisture and oxygen controls on degradation, relation of acid generation and salinity

Modelling at IBC scale – validate upscaling from lab, improve hydrology, validate long-term predictions (continue selected IBCs)

# Thank you

A/Professor Mansour Edraki
Sustainable Minerals Institute
m.edraki@cmlr.uq.edu.au
07 33464060
0407745224

# RGS 2019 CASE STUDIES

## Dr Alan M Robertson – Director/Principal Geochemist - RGS
## Dr Greg Maddocks – Principal Hydrogeochemist - RGS
## Neil Tyson – Business Development Manag Deswik

**Mini-Symposium on AMD Management**
**Sustainable Mineral Institute**
**University of Queensland**
**Thursday 2 May 2019**

## RGS 2019 case studies:

1. Geoenvironmental Block Model - Greg Maddocks
2. 3D Waste Rock Dump Scheduling and Design – Neil Tyson

# Progressive Rehabilitation and Closure Plan Requirements

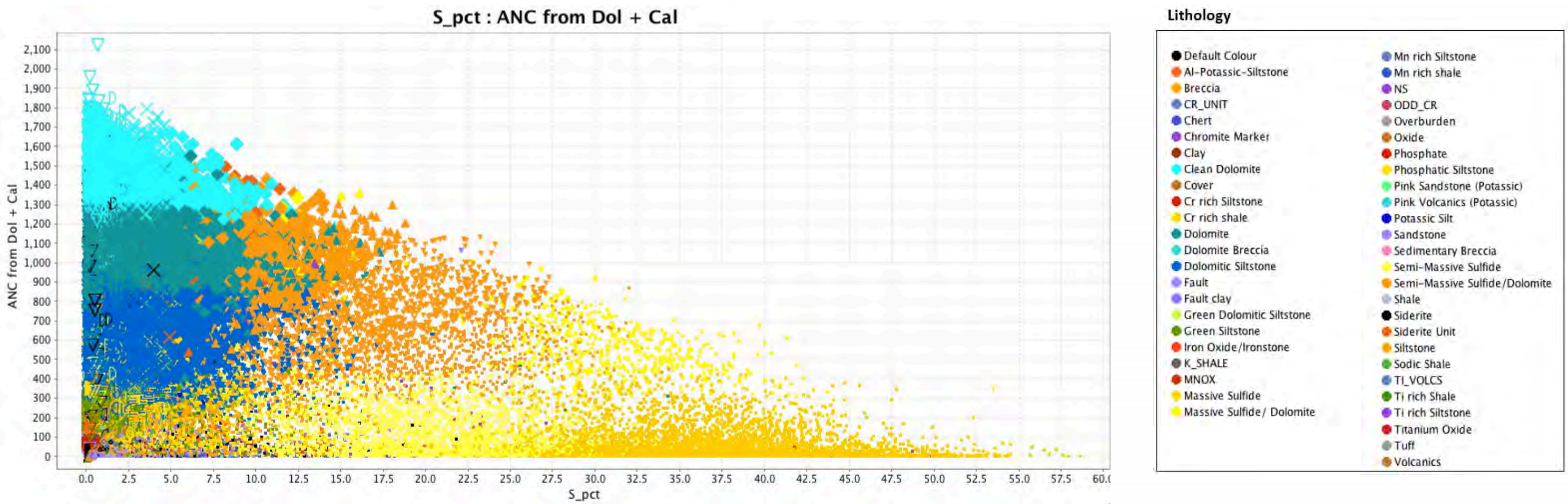
## The Queensland Department of Environment and Science has enacted regulatory changes designed to reduce environmental and financial liability of mining projects

- **A rehabilitation planning component**:
  - the proposed design of the mine,
  - the final landform including encapsulation and cover design requirements,
  - different post-mining land uses or non-use management areas,
  - methodologies and trials for rehabilitation and,
  - any post-closure management requirements.

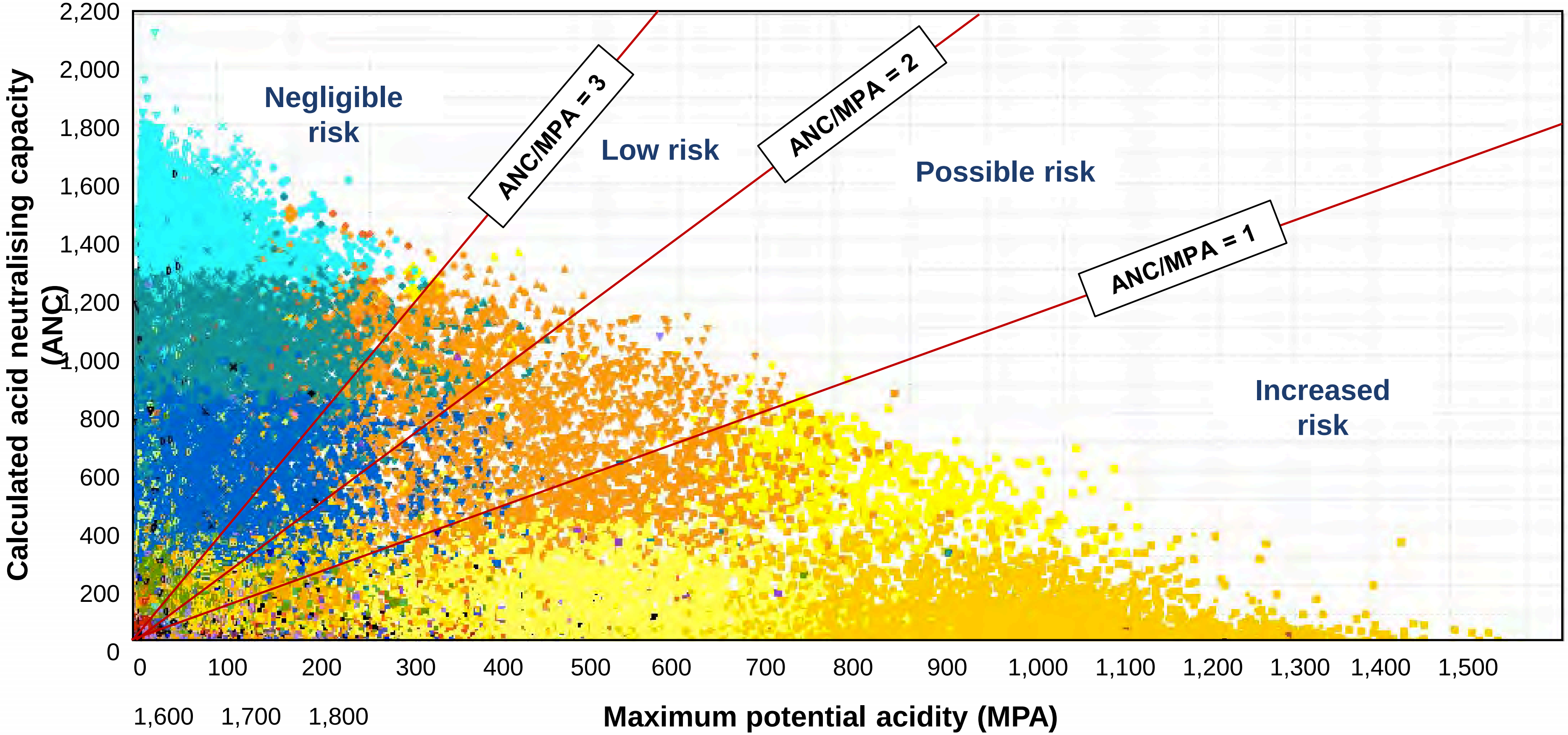
- **A progressive rehabilitation and closure plan schedule:**
  - all mined units (not just waste),
  - maps of final rehabilitation outcomes for each area,
  - tables of time-based milestones for achieving each post-mining land use or non-use management areas, and,
  - any conditions imposed on the schedule by the administering authority.

# Metalliferous Project - Queensland

- There is a lithological and lithogeochemical model with the assay database
- > 70 000 data points in ore and waste zones from > 300 drill holes at a 25 m drill hole density.
- All data points include a full suite of multi-element assay data (ALS Minerals Suite Method ME-MS61).
- 300 data points used to develop correlation between total Ca and Mg and ANC.
- Correlation was used to develop inferred ANC values for the entire database.
- Static and kinetic testing (14 material types) on major lithogeochemical units including AF to AC materials.



# Neutralising potential ratio



# Acid base block model rules

| Acid-base class | Sulfur % | Neutralising potential ratio* | Net acid producing potential* | Description | Percentage of data points |
|---|---|---|---|---|---|
| 1 | ≤0.1 | ≥3 | <-250 | Acid consuming (AC) | 0.8 |
| 2 | ≤0.1 | ≥3 | >-250 | Non Acid Forming Barren (NAF-b) | 5.8 |
| 3 | 0.1-1 | ≥3 | >-50 | Non Acid Forming (NAF) | 16.3 |
| 4 | 0.1-1 | <3 | <-50 | Non Acid Forming saline potential (NAF-s) | 6.0 |
| 5 | 1-2.5 | ≥3 | <-250 | Potentially Acid Forming (PAF) | 4.5 |
| 6 | 1-2.5 | ≥2 | -50 to -250 | Potentially Acid Forming (PAF) | 1.9 |
| 7 | 1-2.5 | <2 | >-50 | Potentially Acid Forming (PAF) | 7.3 |
| 8 | 2.5-5 | <2 | >-125 | Potentially Acid Forming (PAF) | 3.7 |
| 9 | 2.5-5 | ≥2 | > - 250 | Potentially Acid Forming (PAF) | 1.0 |
| 10 | 2.5-5 | ≥3 | > -1,700 | Acid Forming - low capacity (AF-lc) | 5.4 |
| 11 | >5 | ≥3 | ≤ -300 | Acid Forming - low capacity (AF-lc) | 5.2 |
| 12 | >5 | 2-3 | ≤ -150 | Acid forming (AF) | 2.5 |
| 13 | >5 | 1-2 | ≤ 0 | Acid Forming - high capacity (AF-hc) | 5.1 |
| 14 | >5 | ≤1 | > 0 | Extremely acid forming (EAF) | 34.4 |

** Calculated from assay data and calculated ANC coefficients*

- Classification gives each data point a number between 1 and 14 which can then be propagated using GS3™ modelling software and imported into a Surpac ™ block model.
- This will allow for definition of blocks from acid consuming to acid forming.
- Blocks can then be used to build an geoenvironmental block model, and then proposed to be scheduled using mine scheduling software to develop a 3D waste rock dump (WRD) model.

# Next steps

- Run the 14 material types in SURPAC.
- Develop material balances for the 14 material types within the ore, low grade, waste and beneficial materials that can be used for rehabilitation and construction.
- Reduce acid-base classes into something manageable for mine planning and WRD design.
- Metal leaching potential rules (based on total elemental content) are applied to AC, NAF, NAF-B and NAF-S classes to verify if material being used for rehabilitation or construction is contaminated with As, Cd or Tl.
- Verify mobility of total As, Cd and Tl in AC, and NAF units using KLC testing.
- Physical criteria are applied to AC and NAF units to quantify % of material as extremely weathered regolith through to fresh rock using hardness and weathering data in the geological logs. It is necessary to determine how much NAF (for example):
  - is hard rock and can be used to line drains; and,
  - is extremely weathered regolith and can be reserved for soil covers.
- Use geo-environmental block model outputs in Deswik to schedule WRD (and tailings) management options

Deswik

Delivering mining efficiency

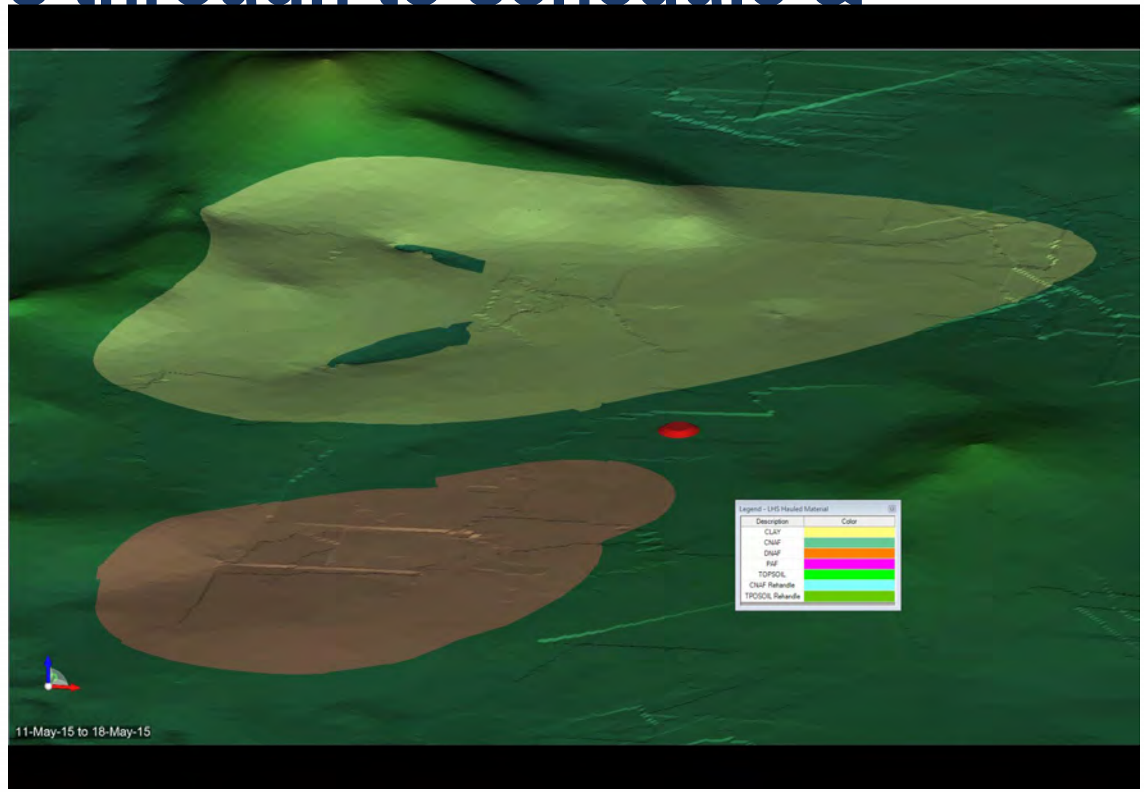
# Integrating Mining, Materials, Landform & Water Planning

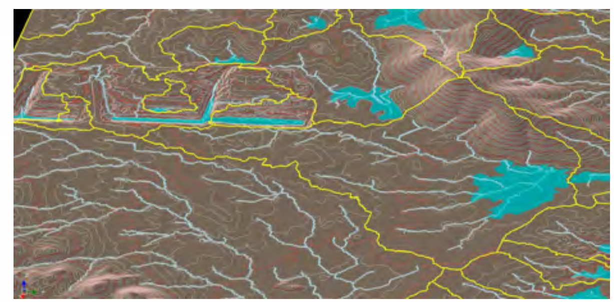
Deswik.Enviro

Environment, sustainability & mine closure

# Geochem metadata flows through to schedule & options evaluation

- Construct a block model for the pit that includes geochemical and physical attributes.
- Use the block model to construct 3D design options for a WRD
- When there is a detailed design for the WRD it can be used to evaluate probable environmental performance
- **Integrate production plan and WRD construction**

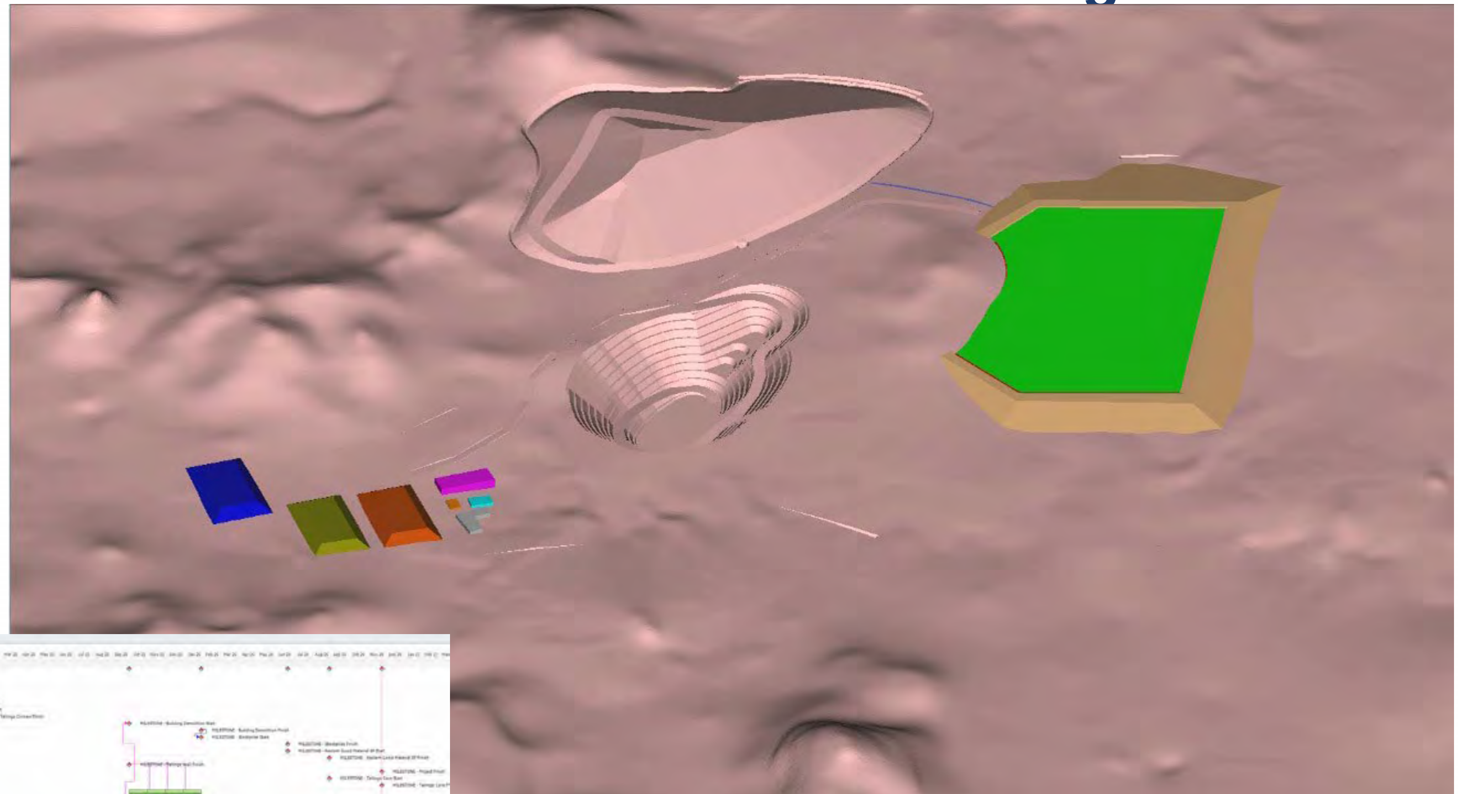


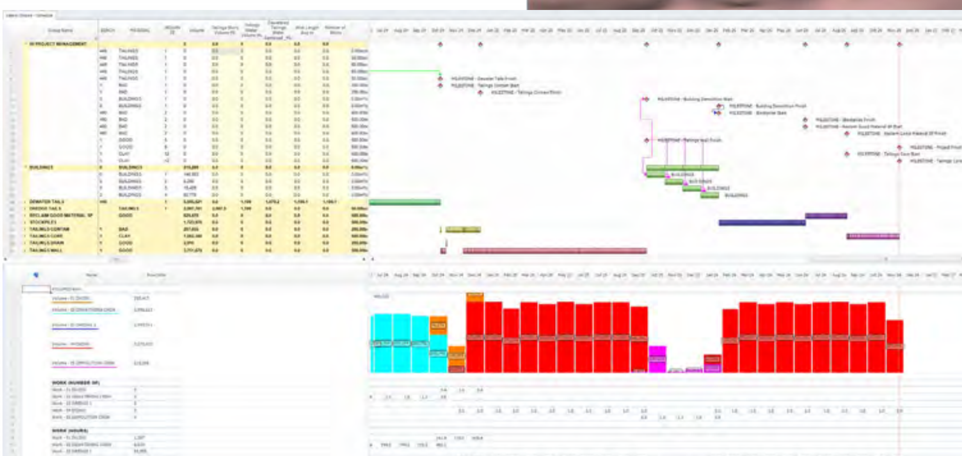



# Integration Allows Optimization

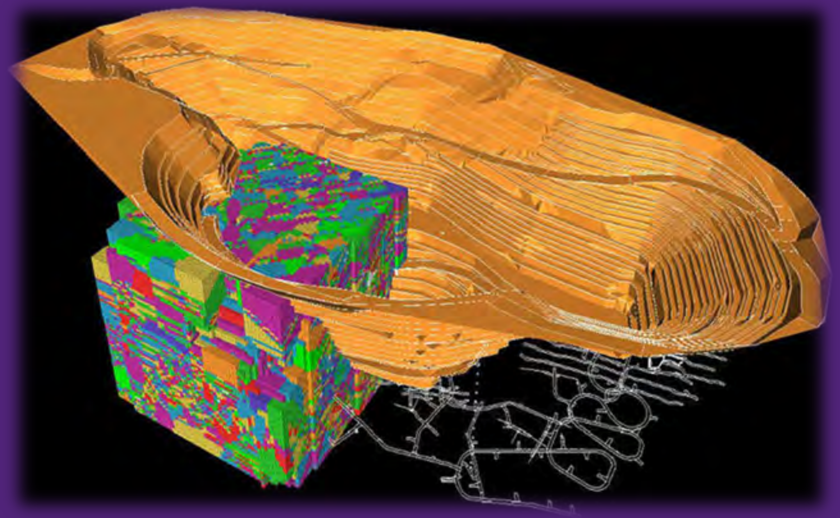
- Water
- Final landform
- Tailings
- Pollutants
- Rehabilitation scheduling
- Closure costing & overall liability estimate
- Feedback to Reserves (Decision to Mine)

# Use The Same Tools Mine Planners Use Delivers Integrated Plans





# Applications of geometallurgy for waste characterisation across the mining value chain



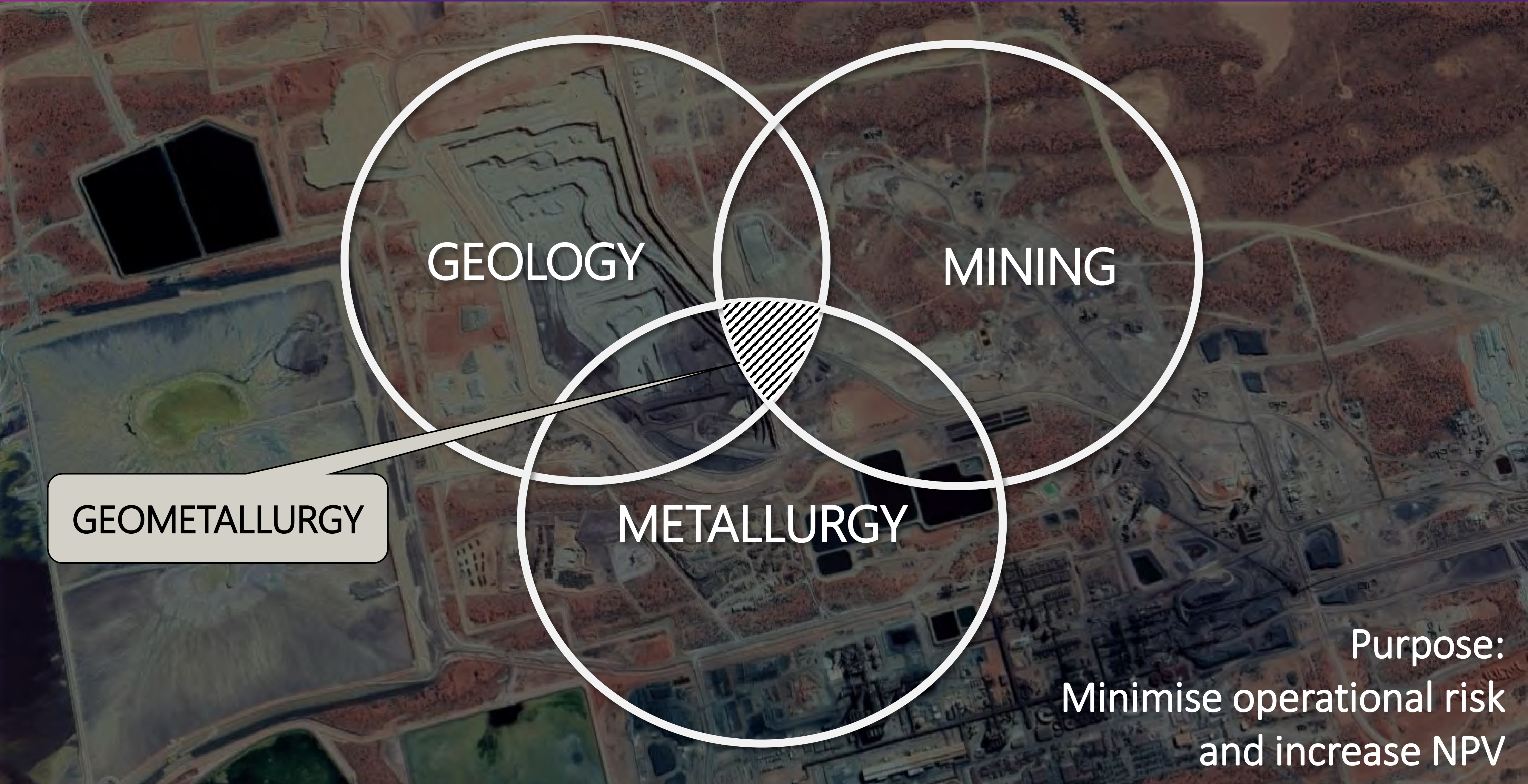

Dr Anita Parbhakar-Fox

Senior Research Fellow

WH Bryan Mining and Geology Research Centre, SMI, UQ

# What is ‘geometallurgy’?

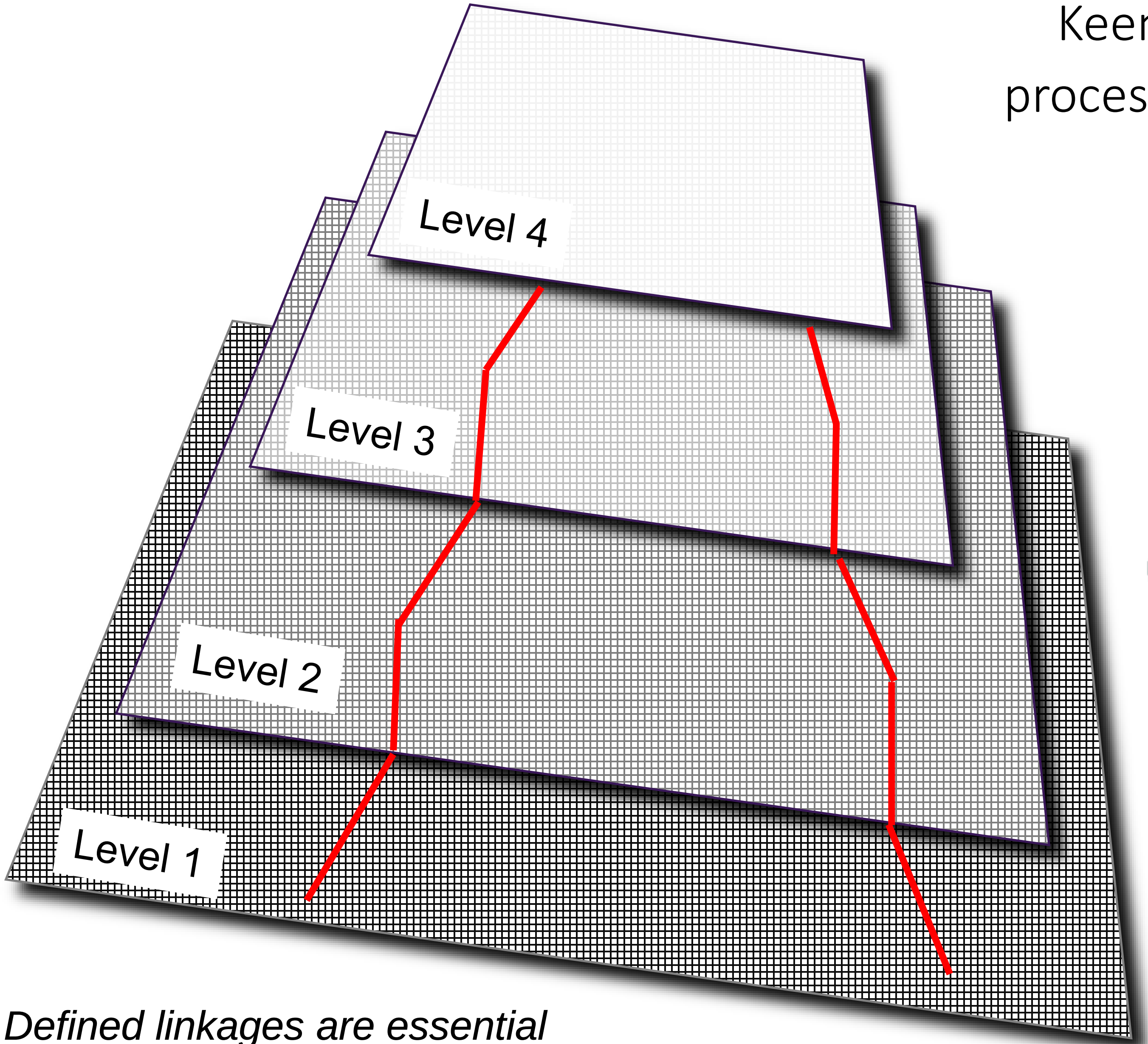
The University of Queensland
Australia

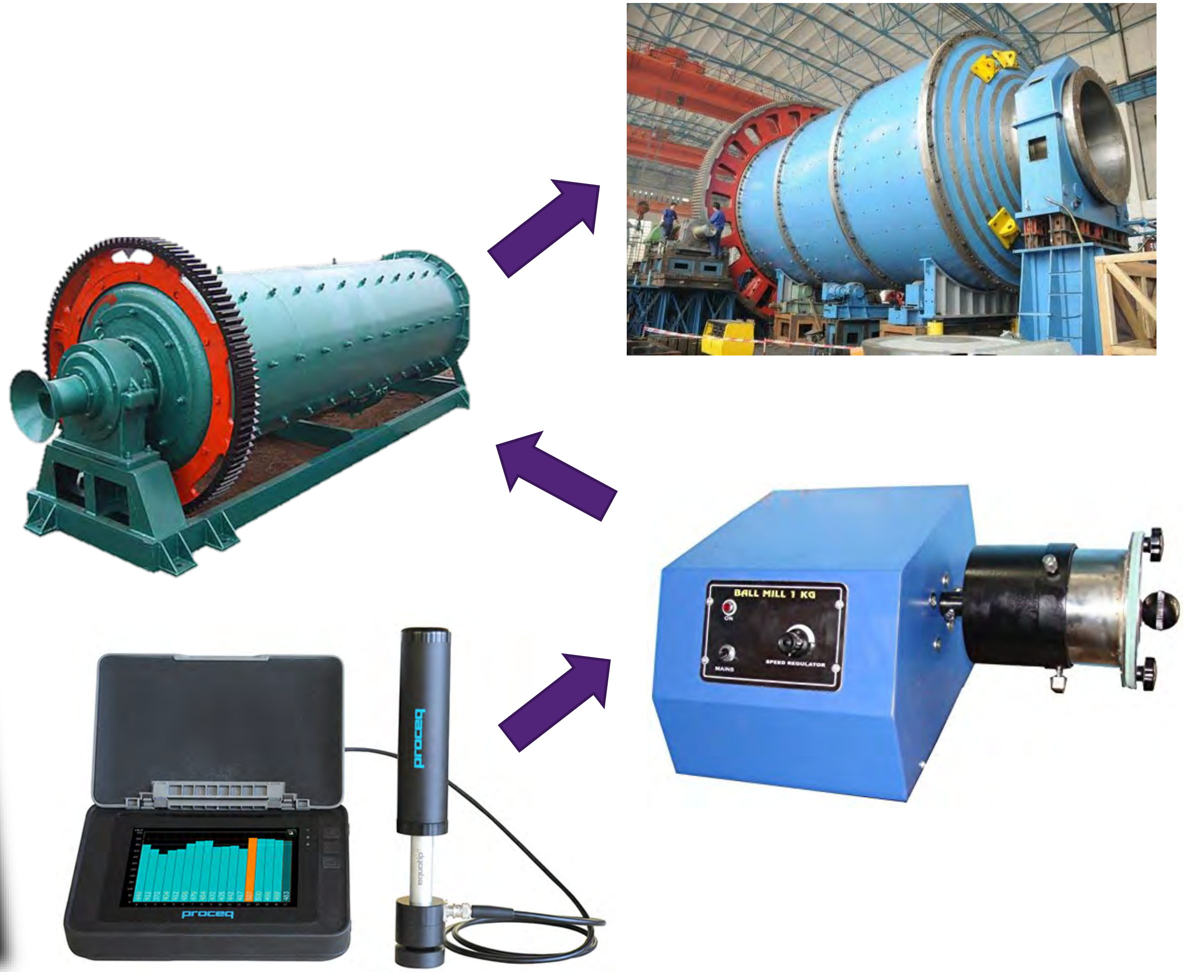



Purpose:
Minimise operational risk and increase NPV

# Geometallurgy Matrix concept

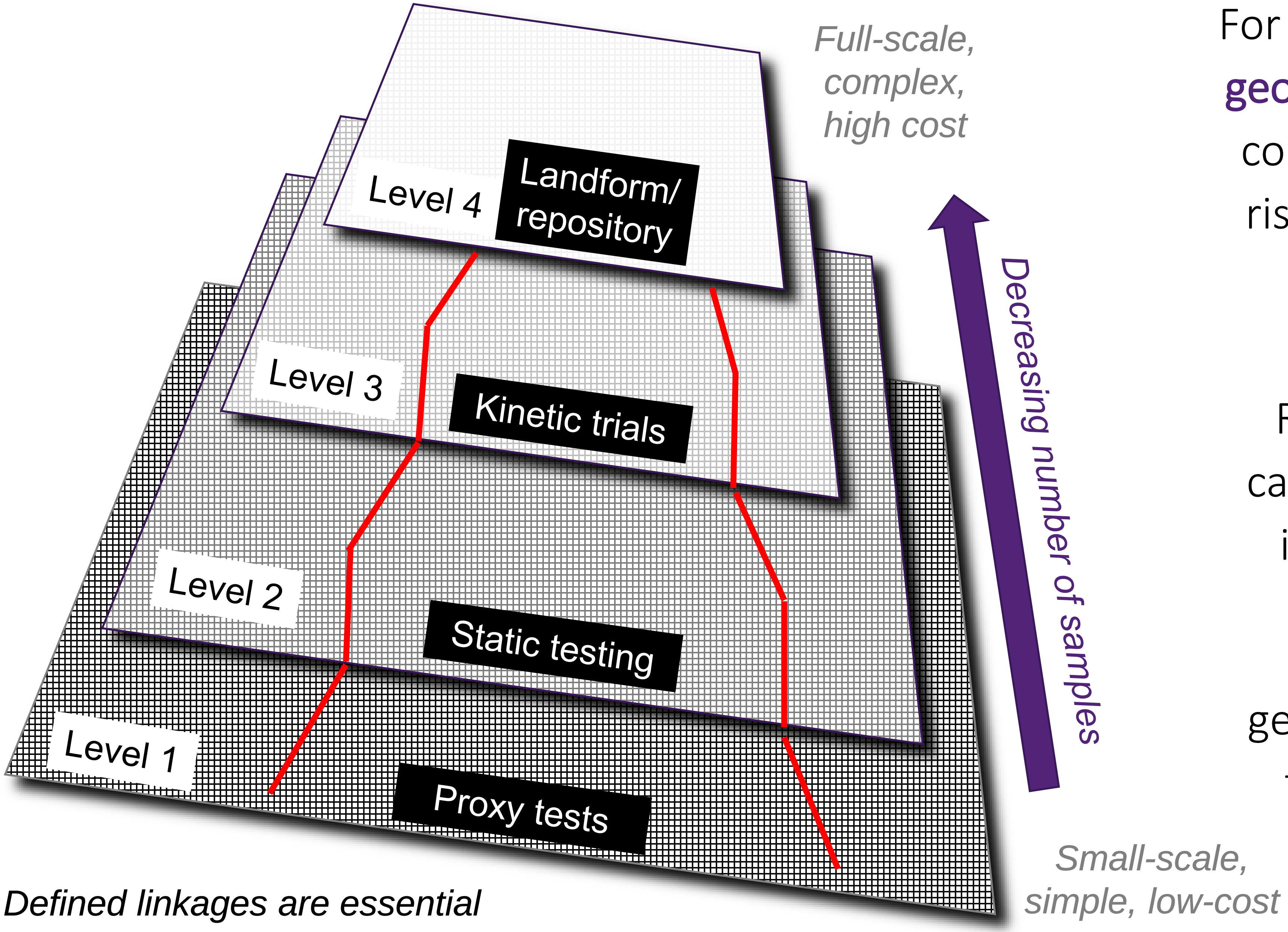
Keeney (2008): Aim is to propagate measured processing attributes (i.e. A*b, BMWI) down in the matrix to Level 2 and Level 1




*Defined linkages are essential*

# Geometallurgy Matrix concept




*Defined linkages are essential*

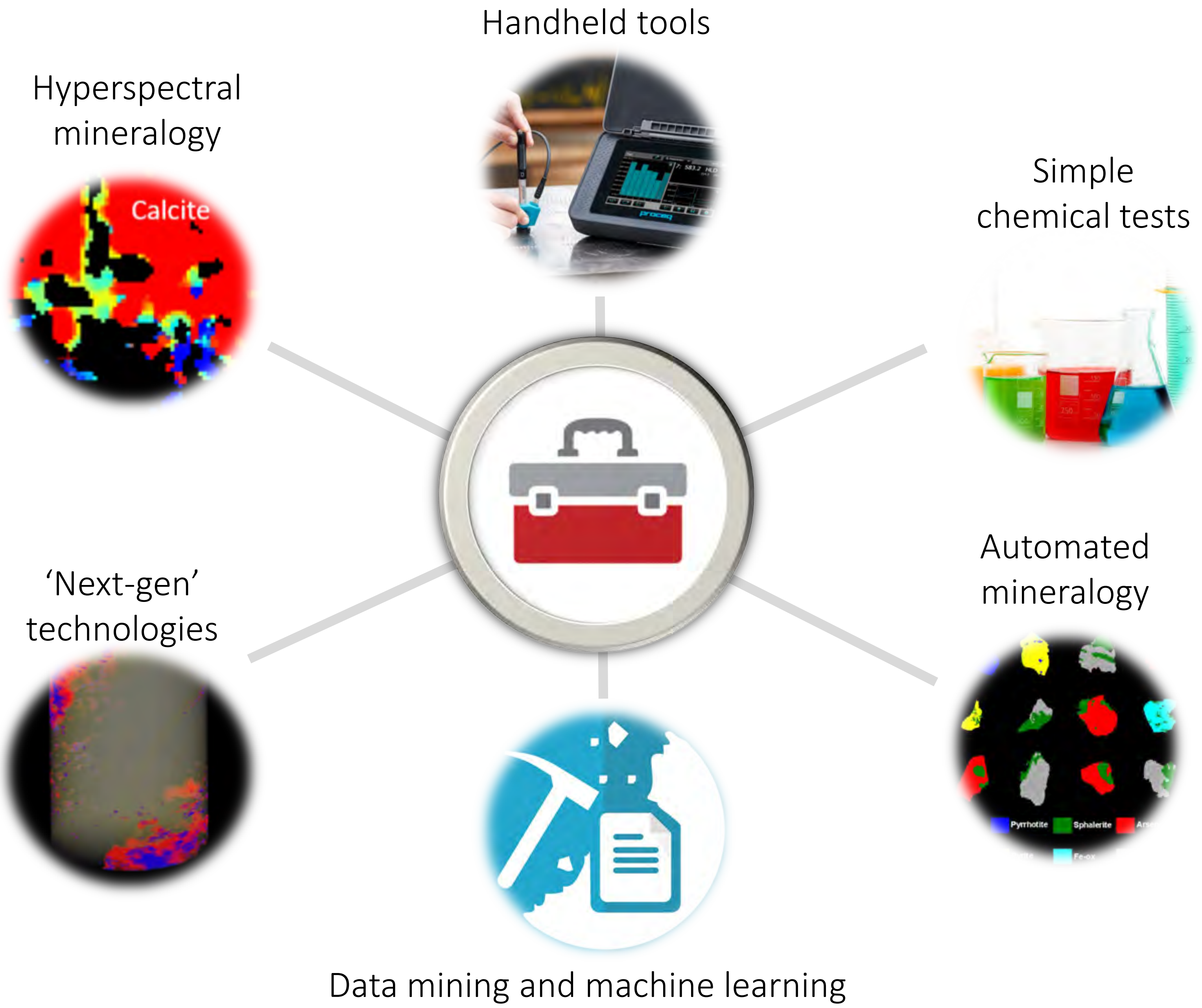
For mine waste characterisation a **geometallurgical matrix approach** could be readily adopted to de-risk projects and improve long-term financial outcomes

Representative sampling and capturing heterogeneity is a key issue- this helps overcome it

Requires the embedding of geoenvironmental proxy tests at the earliest LOM stages (i.e., exploration/prefeasibility)

# The (enviro)geometallurgy tool kit

The University of Queensland
AUSTRALIA



# Hyperspectral mineralogy



- Challenges encountered when collecting 'representative' geoenvironmental samples at early life-of-mine stages
- Increasing ore deposit knowledge will assist with static and kinetic testing sample selection
- Hyperspectral data measuring VNIR and SWIR active minerals (e.g., Corescan) and TIR (e.g., HyLogger)
- Corescan: ~2,000 m can be collected per day
- Value-add opportunity by perform geoenvironmental domaining to support waste forecasting
- Identify potentially acid forming, non-acid forming and neutralising domains to enable waste management through early forecasting of geoenvironmental characteristics

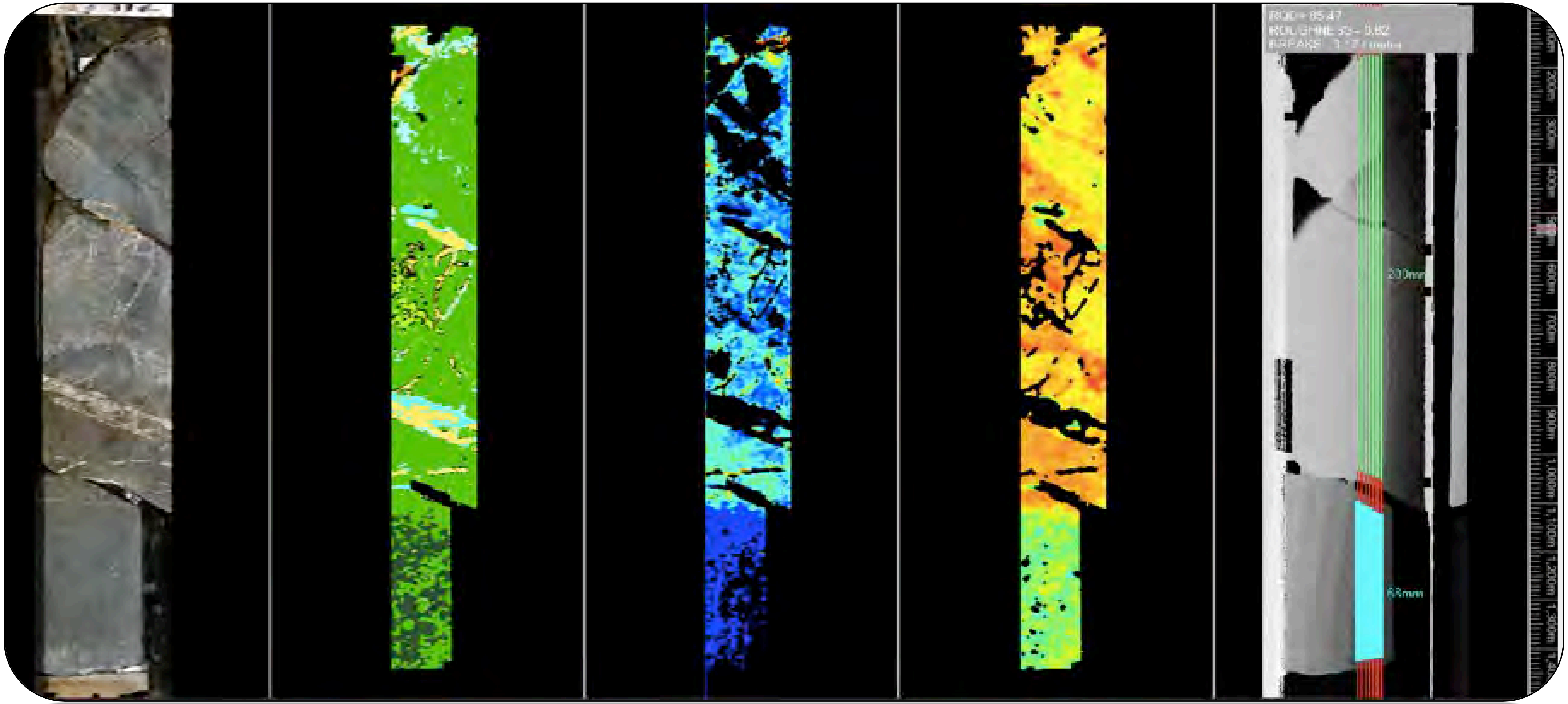
# Hyperspectral mineralogy

| Type | Silicate Structure | Mineral Group | Example | VNIR Response | SWIR Response | TIR Response |
|---|---|---|---|---|---|---|
| Silicates | Inosilicates | Amphibole | Actinolite | Non-diagnostic | Good | Good |
| | | Pyroxene | Diopside | Good | Moderate | Good |
| | Cyclosilicates | Tourmaline | Dravite | Non-diagnostic | Good | Moderate |
| | Neosilicates | Garnet | Grossular | Moderate | Non-diagnostic | Good |
| | | Olivine | Foresterite | Good | Non-diagnostic | Good |
| | Sorosilicates | Epidote | Clinozoisite | Non-diagnostic | Good | Good |
| | Phyllosilicates | Mica | Muscovite | Non-diagnostic | Good | Moderate |
| | | Chlorite | Chlinochlore | Non-diagnostic | Good | Moderate |
| | | Clay minerals | Illite | Non-diagnostic | Good | Moderate |
| | | | Kaolinite | Non-diagnostic | Good | Moderate |
| | Tectosilicates | Feldspar | Orthoclase | Non-diagnostic | Non-diagnostic | Good |
| | | | Albite | Non-diagnostic | Non-diagnostic | Good |
| | | Silica | Quartz | Non-diagnostic | Non-diagnostic | Good |
| Non-silicates | Carbonates | Calcite | Calcite | Non-diagnostic | Good | Good |
| | | Dolomite | Dolomite | Non-diagnostic | Good | Good |
| | Hydroxides | | Gibbsite | Non-diagnostic | Good | Moderate |
| | Sulfates | Alunite | Alunite | Moderate | Good | Moderate |
| | | | Gypsum | Non-diagnostic | Good | Good |
| | Borates | | Borax | Non-diagnostic | Good | Uncertain |
| | Halides | Chlorides | Halite | Non-diagnostic | Moderate | Uncertain |
| | Phosphates | Apatite | Apatite | Moderate | Moderate | Good |
| | Oxides | Hematite | Hematite | Good | Non-diagnostic | Non-diagnostic |
| | | Spinel | Chromite | Non-diagnostic | Non-diagnostic | Non-diagnostic |
| | Sulfides | | Pyrite | Non-diagnostic | Non-diagnostic | Non-diagnostic |

*Linton et al. (2018)*

# Hyperspectral mineralogy

THE UNIVERSITY OF QUEENSLAND AUSTRALIA




Core photography | Mineral Class map | Chlorite wavelength position | Chlorite match intensity | Geotechnical parameters

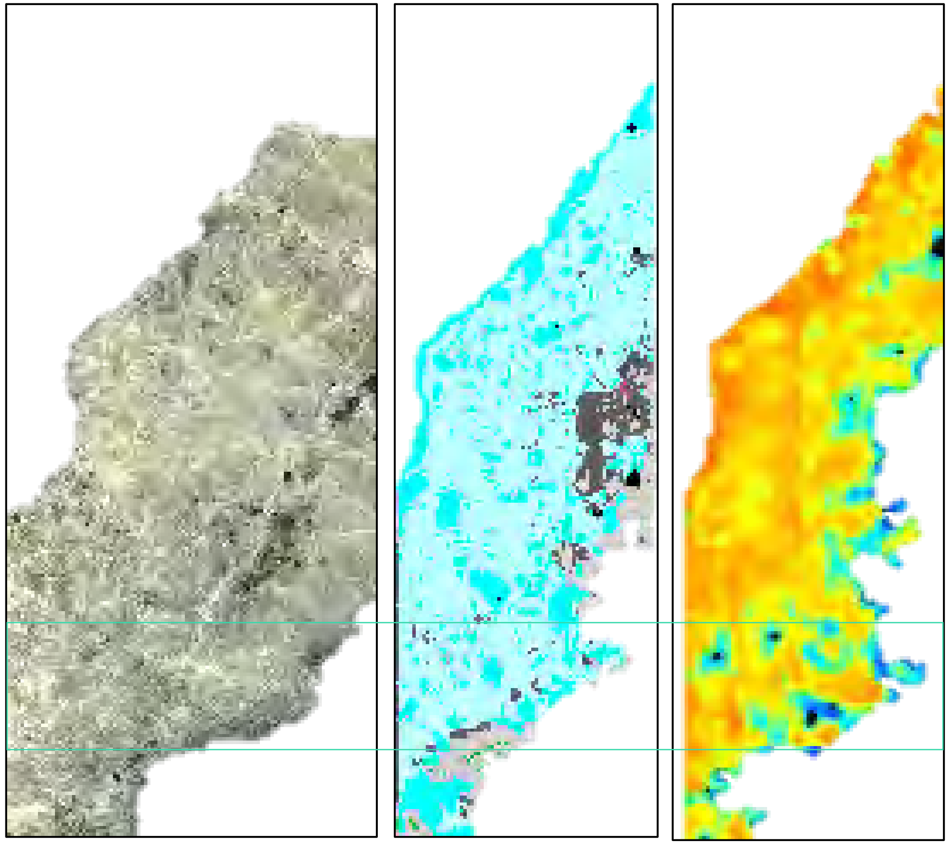
TMVC TRANSFORMING THE MINING VALUE CHAIN

NEWCREST MINING LIMITED

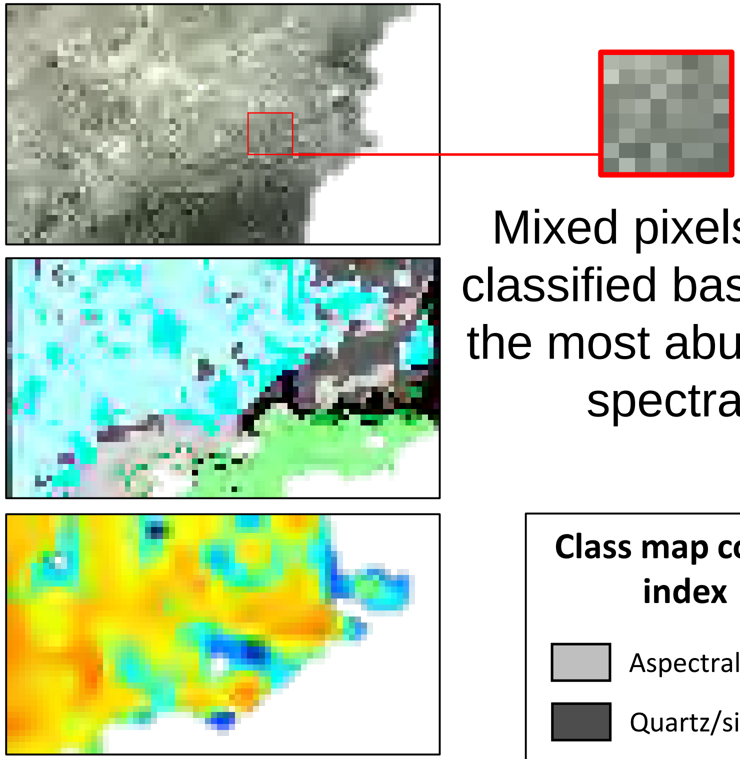
corescan

# Hyperspectral mineralogy

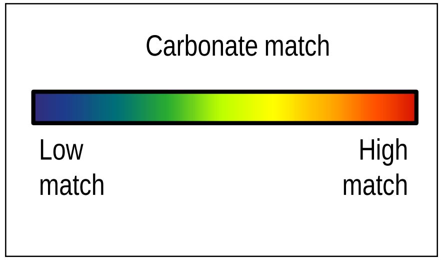




Core photography | Mineral map | Carbonate match



Mixed pixels are classified based on the most abundant spectra




**Class map colour index**

- Aspectral
- Quartz/silica
- Quartz-carbonate
- Carbonate
- Sericite
- Sericite + chlorite
- Chlorite
- Clinochlore

# Hyperspectral mineralogy

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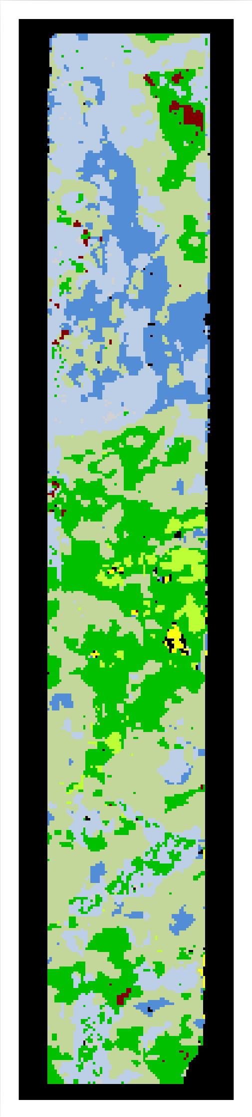
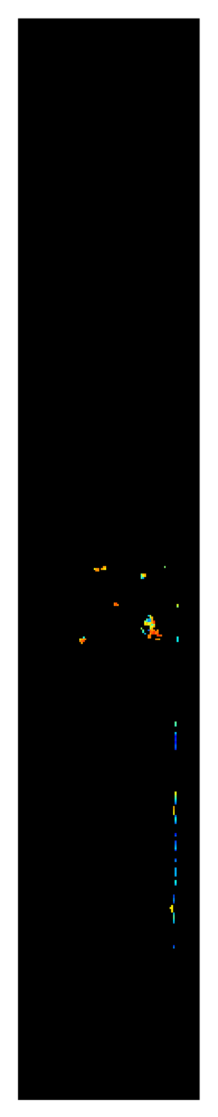
Core photography

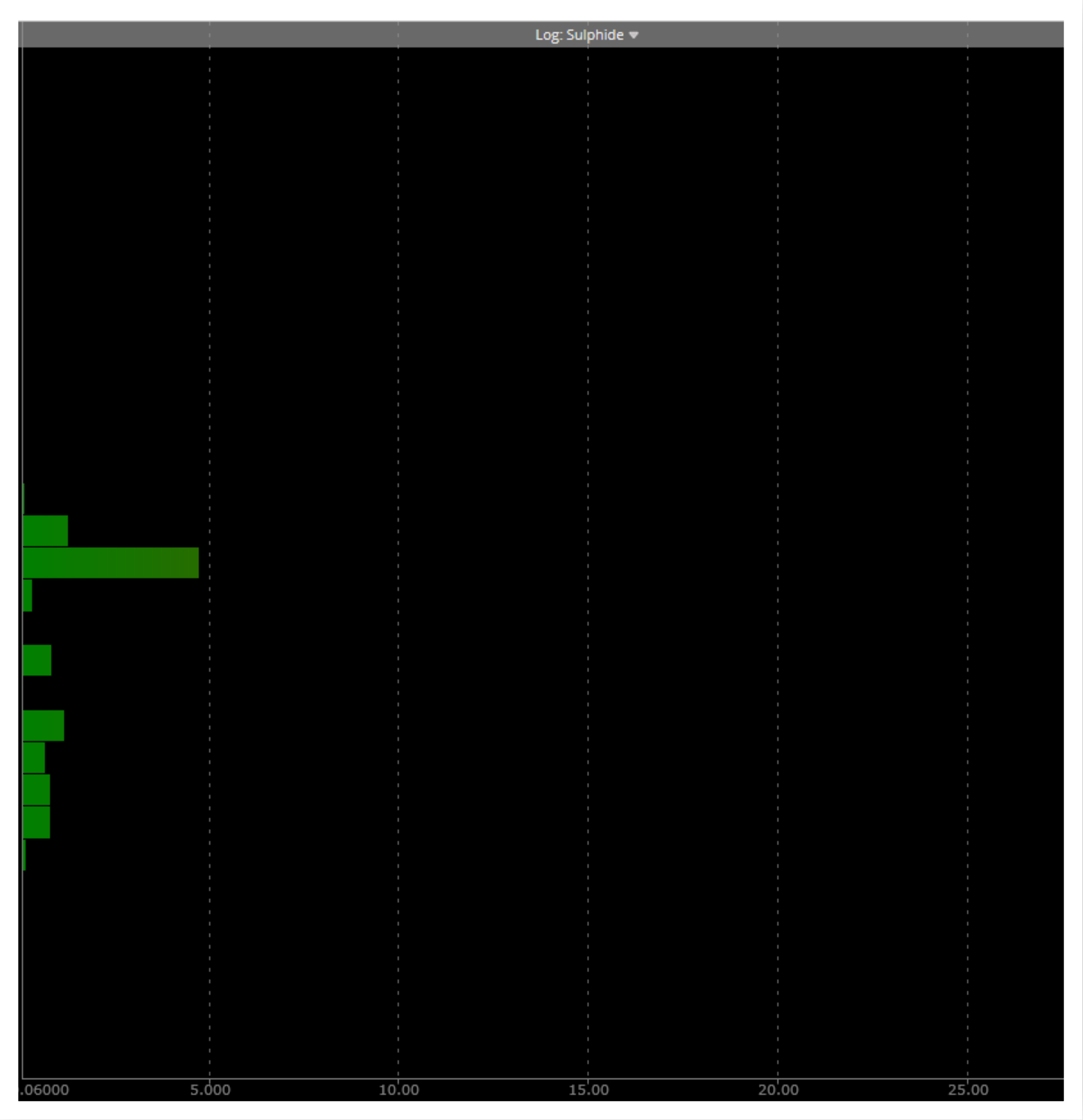
Mineral class map



Sulfide distribution



Log Sulfide distribution

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# Hyperspectral mineralogy

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## Hyperspectral data

**Core images**

**Mineral maps**

## Geoenvironmental Domaining Index (GDI)

**Calculated Mineral abundance** * **Scaled Neutralising Potential/ Acid Potential values** * **Relative reactivity values**

(Jambor et al., 2007; Parbhakar-Fox and Lottermoser, 2014)

(Sverdrup, 1990)

***Example***

| | | | |
|---|---|---|---|
| **Chlorite: 60 %** | * 0.006 | * 0.02 | = 0.00012 |
| **Carbonate: 30 %** | * 1 | * 1 | = 30 |
| **Quartz: 10 %** | * 0 | * 0.004 | = 0 |

***Pixel GDI = ~30***

*Jackson et al. (2018)*

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# Hyperspectral mineralogy

The University of Queensland Australia

## First pass GDI (V2) value risk assessment with sulfides identified defines 5 risk grade classification fields

| GDI value | GDI risk grade | Description of geoenvironmental characteristics |
|---|---|---|
| - 35,000 to -900 | Extreme risk | Dominance of acid forming minerals. Sulfides identified as first mineral > 75 %. No primary neutralisers (AP >>NP). |
| -900 to 0 | High risk | Sulfides common. Sulfides identified as 2nd and 3rd mineral < 75 %. No primary neutralisers (AP >NP). |
| 0 to 10,000 | Potential risk | Dominated by silica/quartz, sericite, chlorite.<br>Few sulfides present, minor primary neutralisers (AP≠NP).<br>Some gypsum present. |
| 10,000 to 40,000 | Low risk | Carbonate abundance < 50 % (AP<NP). |
| 40,000 to 100,000 | Very low risk | Carbonate dominates as first Corescan mineral > 50 %.<br>Long term acid neutralising capacity likely (AP<<NP). |

*Jackson et al. (2018)*

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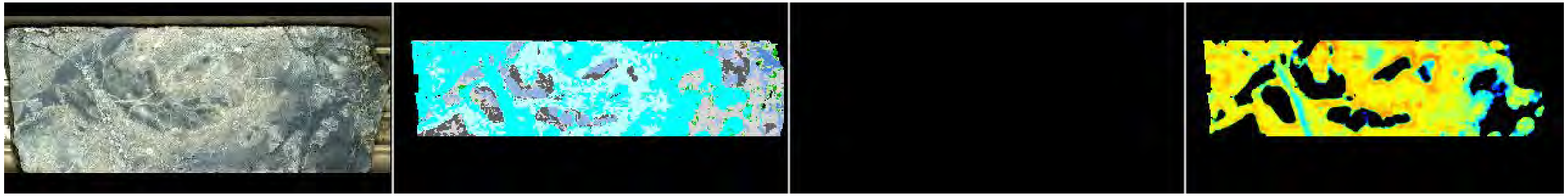
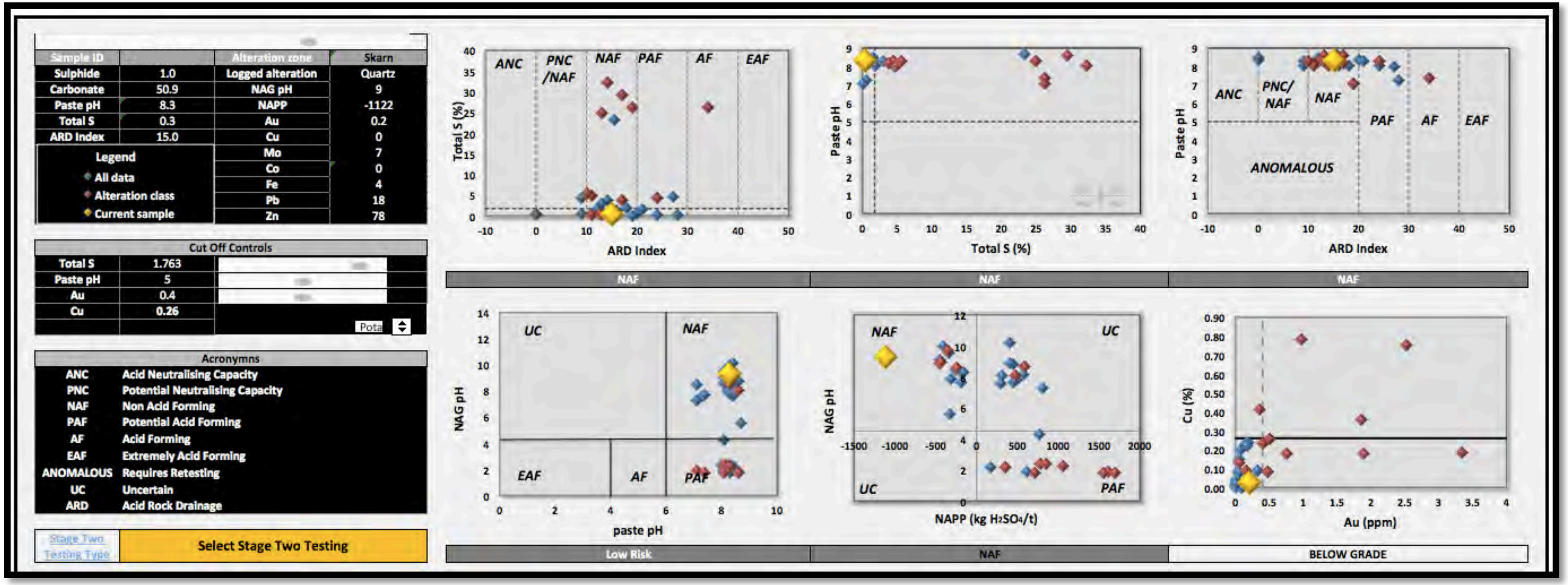
# Hyperspectral mineralogy

## Sample A: Skarn

Core photography | Classified mineral map | Sulfide recognition | Carbonate identification



GDI V2:
34,370
Low risk




Static testing=
NAF
(High ANC)

*Jackson et al. (2018)*

# Hyperspectral mineralogy

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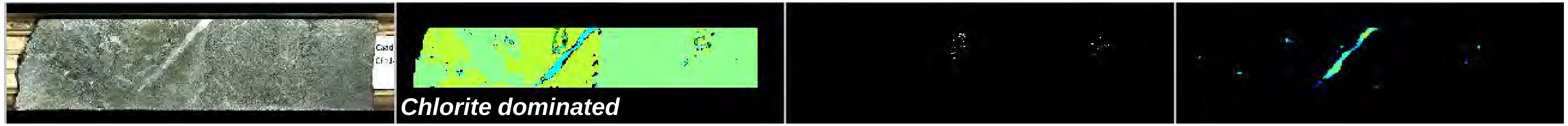
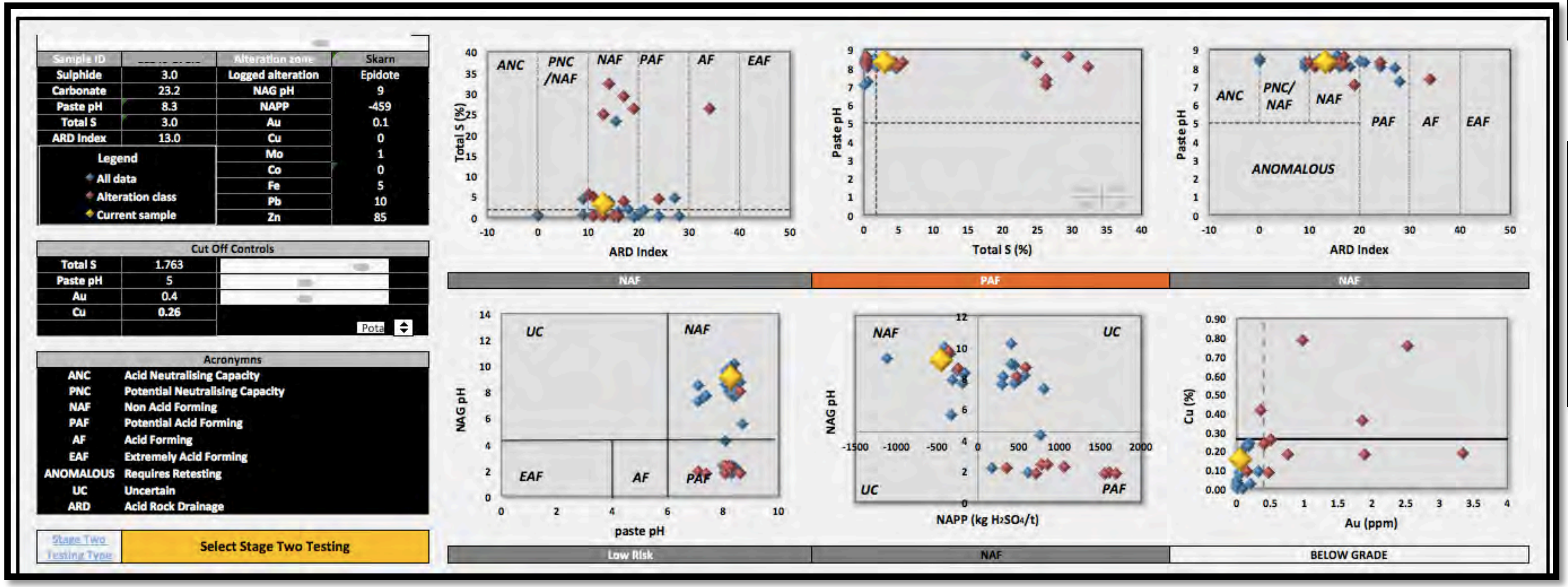
## Sample B: Skarn

Core photography | Classified mineral map | Sulfide recognition | Carbonate identification




**GDI V2:**
1910
Potential risk




Static testing=
NAF (3% sulfide-sulfur; 23% calcite)

*Jackson et al. (2018)*

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# Hyperspectral mineralogy

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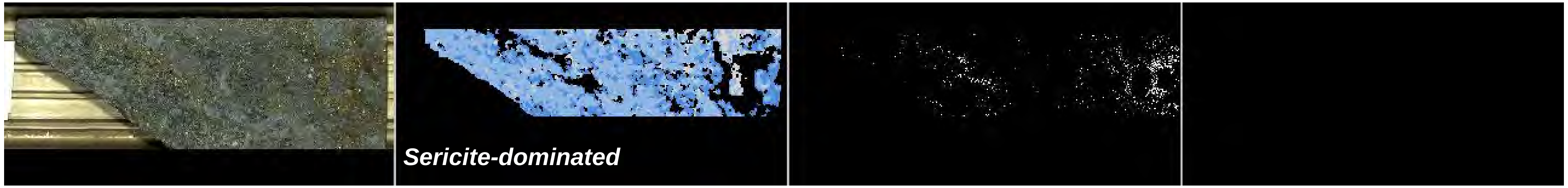
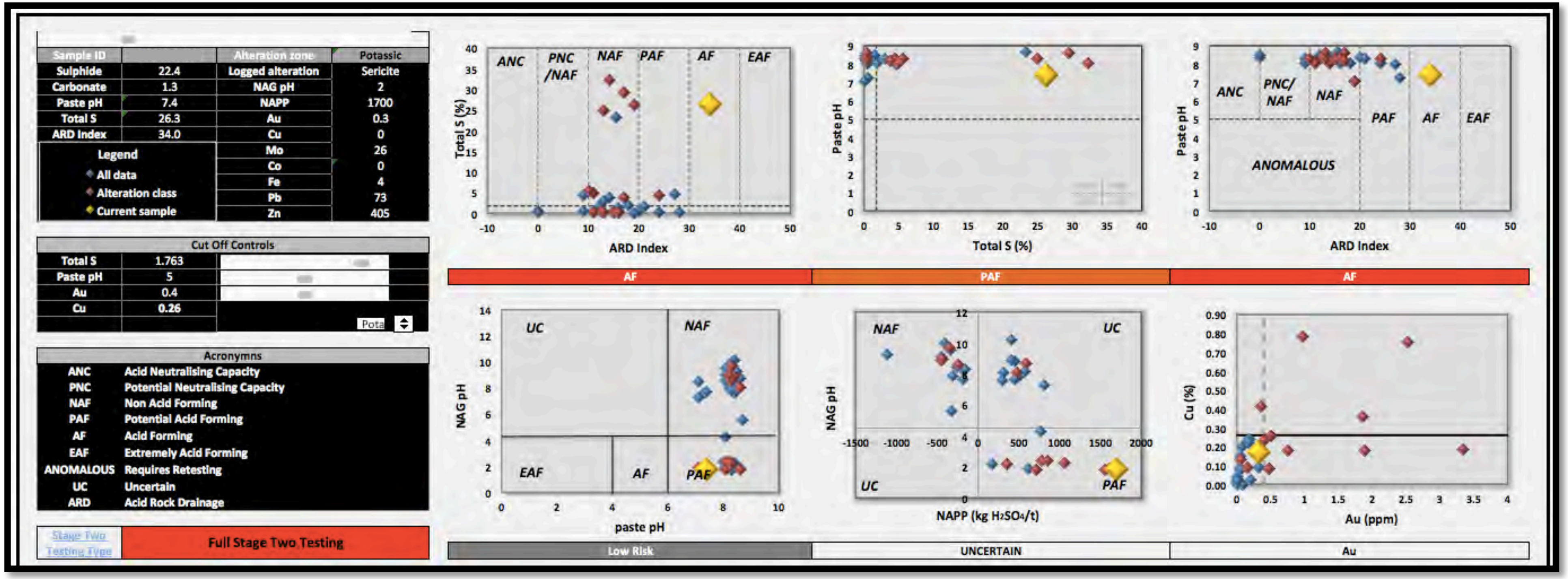
## Sample C: Potassic Zone

Core photography | Classified mineral map | Sulfide recognition | Carbonate identification




GDI V2:
-140=
High risk




Static testing=
PAF/AF

Jackson et al. (2018)

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# Hyperspectral mineralogy

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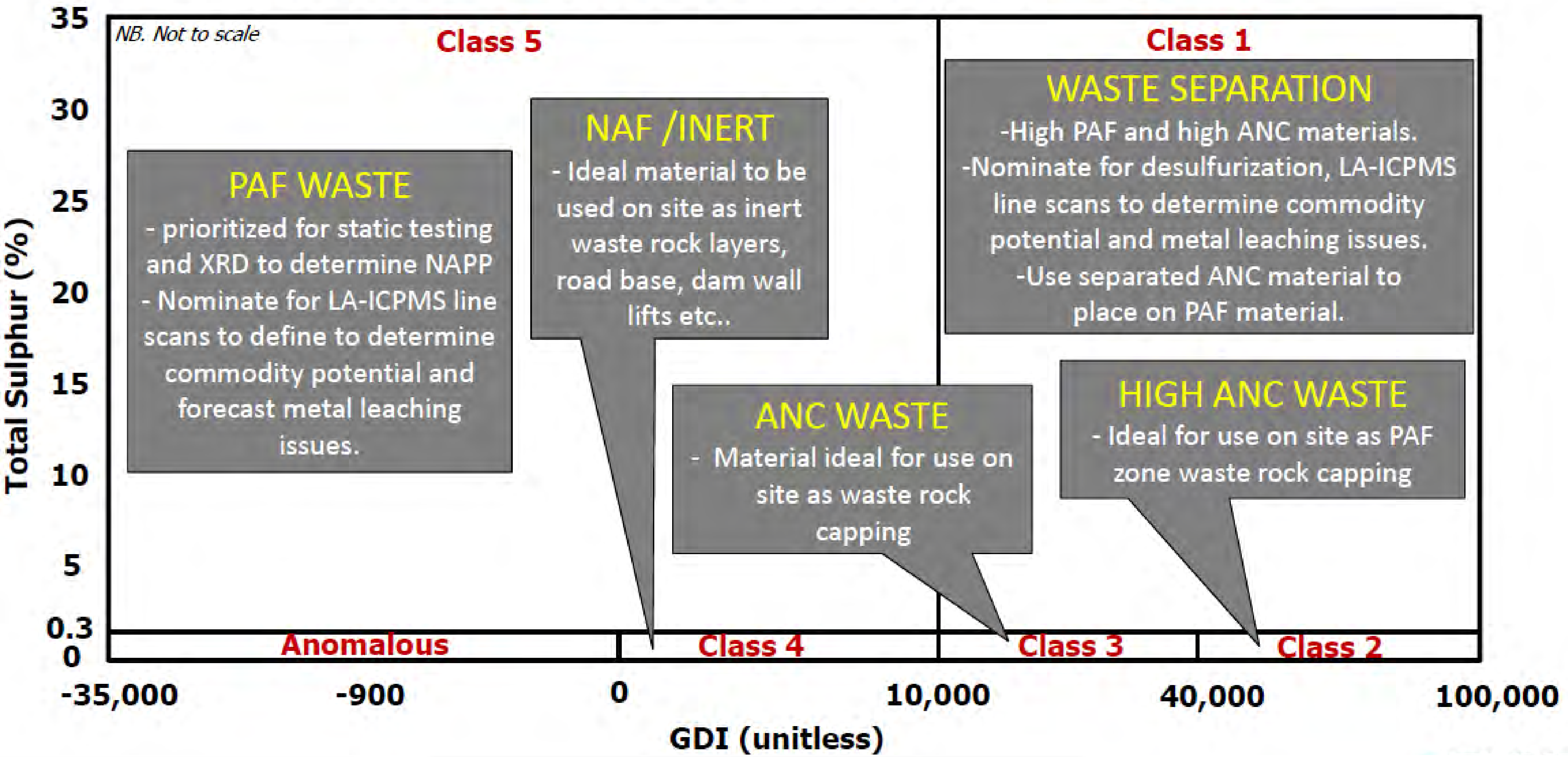


*minerals* MDPI

*Article*

**Forecasting Geoenvironmental Risks: Integrated Applications of Mineralogical and Chemical Data**


Anita Parbhakar-Fox [1,*], Nathan Fox [2], Laura Jackson [1] and Rebekah Cornelius [1]

1 ARC Transforming the Mining Value Chain Industrial Transforming Research Hub, University of Tasmania, Private Bag 79, Hobart, Tasmania 7001, Australia; lauraj0@utas.edu.au (L.J.); rebekah.k.cornelius@gmail.com (R.C.)
2 CRC for Optimising Resource Extraction, University of Tasmania, Private Bag 79, Hobart, Tasmania 7001, Australia; nathan.fox@utas.edu.au
* Correspondence: anitap1@utas.edu.au; Tel.: +61-4-00850831


eCite Digital Repository

**Integrating hyperspectral analysis and mineral chemistry for geoenvironmental prediction**

UTAS Home > Research > eCite > Item

Citation


Jackson, L and Parbhakar-Fox, A and Fox, N and Meffre, S and Cooke, DR and Harris, A and Savinova, E, Integrating hyperspectral analysis and mineral chemistry for geoenvironmental prediction, Proceedings from the 11th International Conference on Acid Rock Drainage International Mine Water Association WISA Mine Water Division, 10-14 September 2018, Pretoria, South Africa, pp. 1075-1080. ISBN 9780620806503 (2018) [Refereed Conference Paper]


Additional applications when scanning column feed materials prior to kinetic testing – results to be published later in 2019

# Handheld tools and chemical tests

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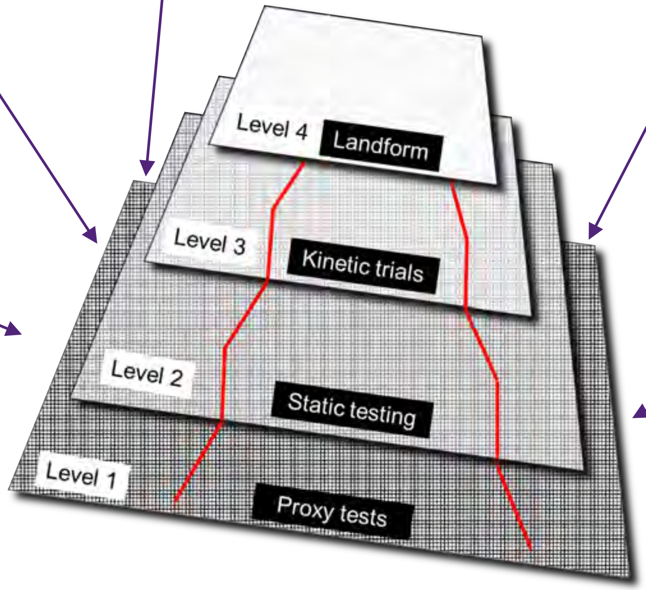
Environmental Logging

Chemical Staining

Hardness measurements

pXRF




Field chemical tests

Not all are new, but not routinely applied for geoenvironmental characterisation

Integration of results provides the best quality information to feed into the geometallurgical matrix

# Handheld tools and chemical tests



## Acid Rock Drainage Index (ARDI)


- Sulphide content: *(0 to 10)*
- Sulphide alteration: *(0 to 10)*
- Sulphide morphology : *(0 to 10)*
- Carbonate content : *(-5 to 10)*
- Mineral association : *(-5 to 10)*

Extremely acid forming

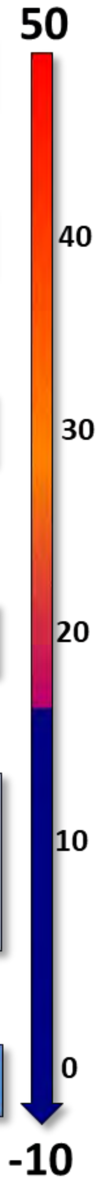
Acid forming

Potentially acid forming

Non-acid forming

Non-acid forming/ potential neutralising capacity

Acid neutralising capacity

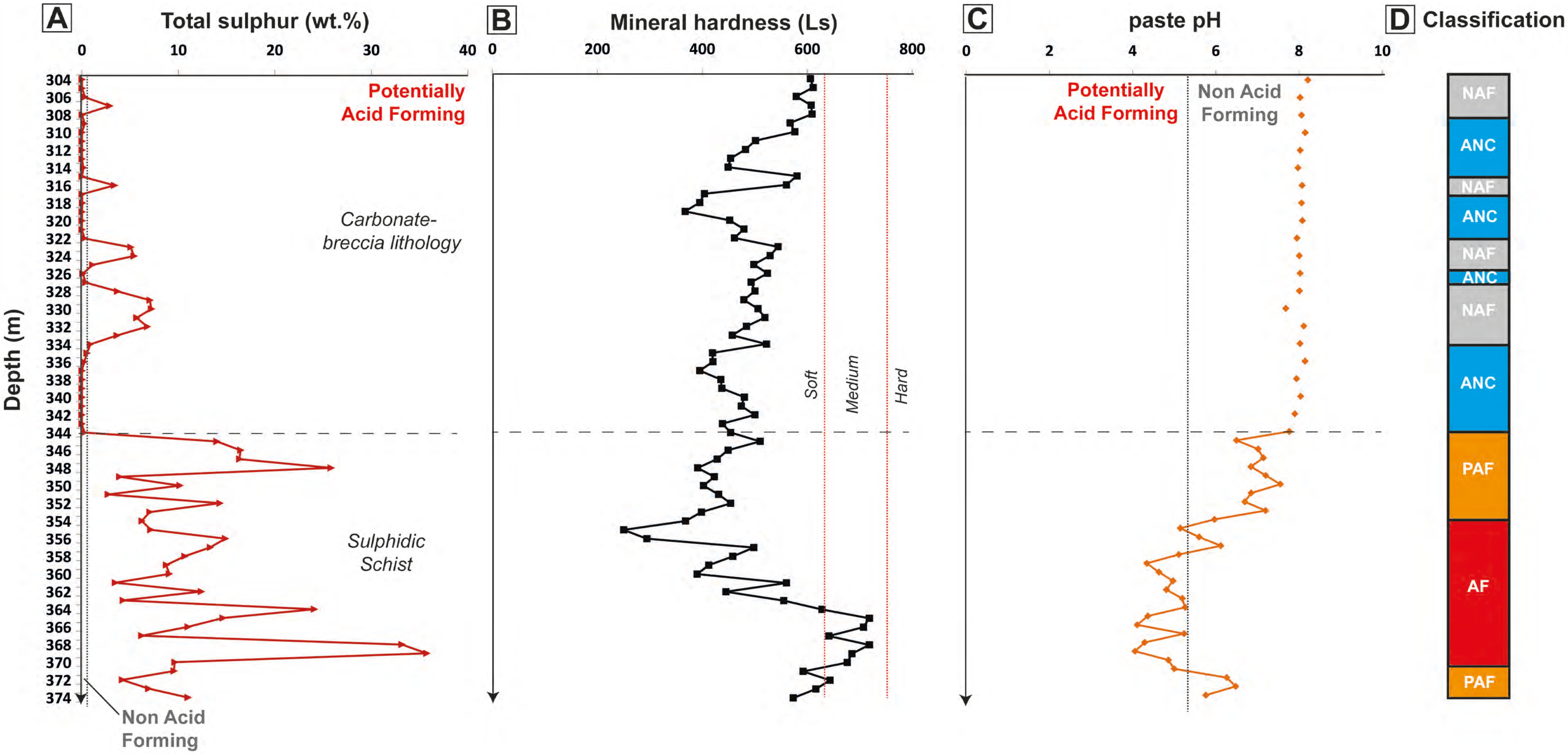



*Parbhakar-Fox et al. (2011; 2018); Opitz et al. (2016); Cornelius et al. (2017)*

# Handheld tools and chemical tests


EQUOtip

Mineral hardness to determine rate of weathering and predict elution of acid/ neutralisation




*Parbhakar-Fox et al. (2015)*

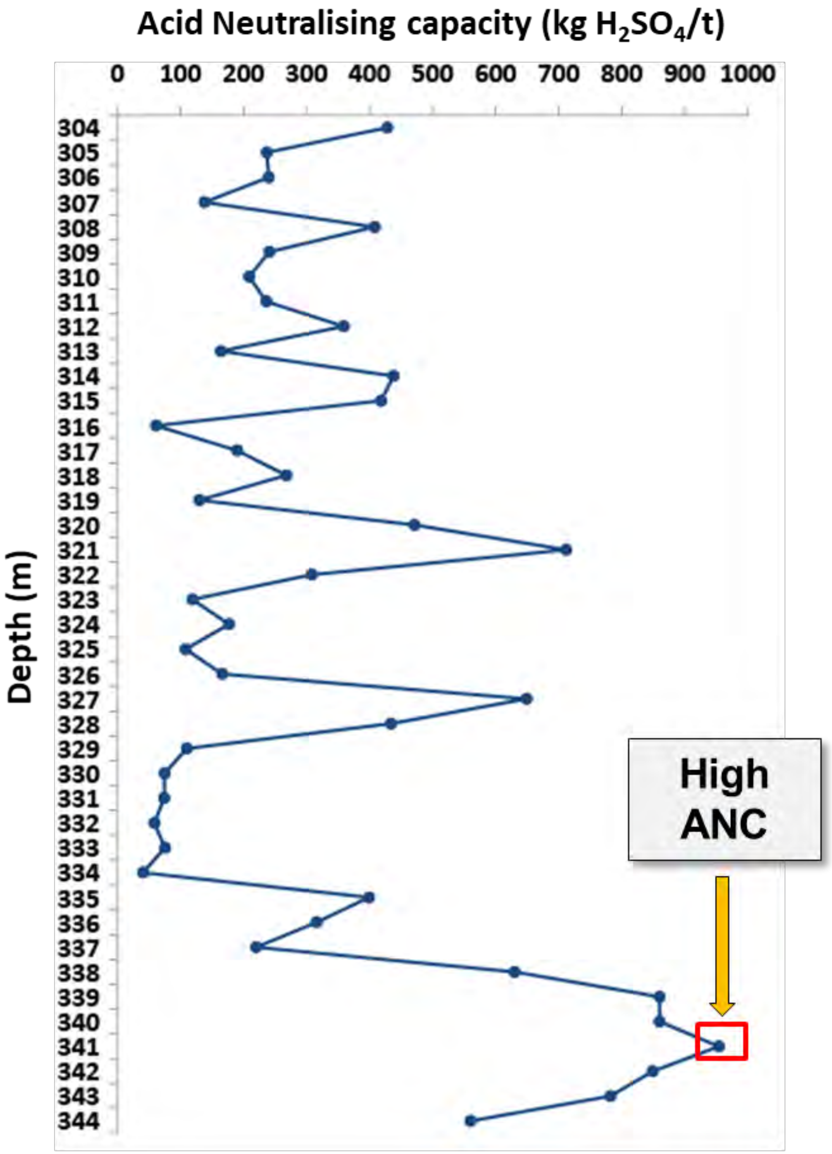
# Handheld tools and chemical tests

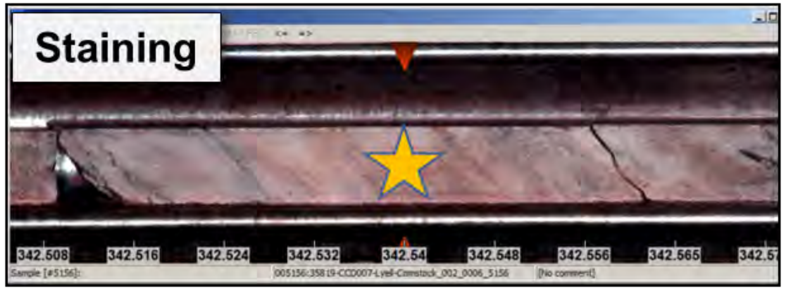
Alizarin Red-S (2g) + Potassium Ferricyanide (2g)

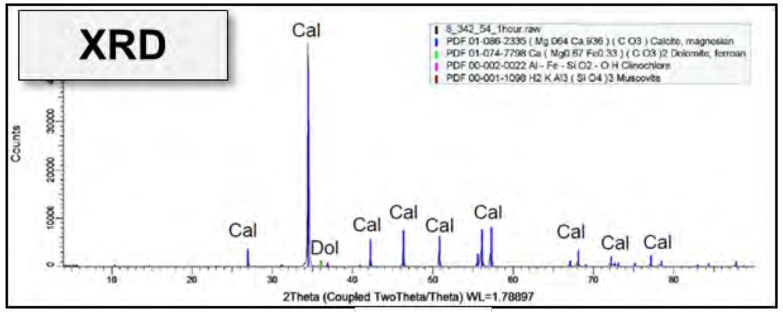
*250 ml HCl (2%)*

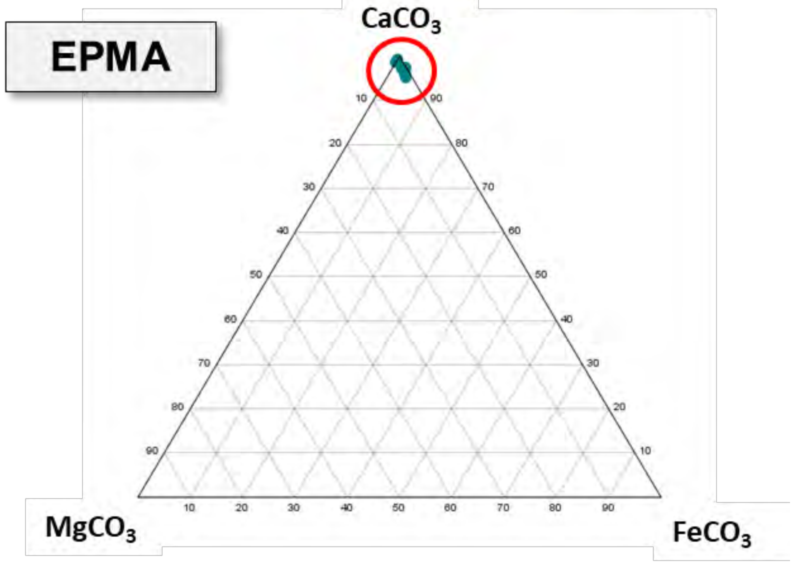
*Apply several coats of stain*

calcite: red | ferroan dolomite: blue



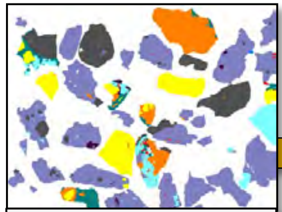




*Parbhakar-Fox et al. (2015)*

# Automated mineralogy



## Mineral Liberation Analyser

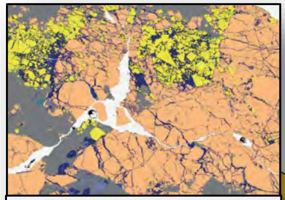


SPL Lite

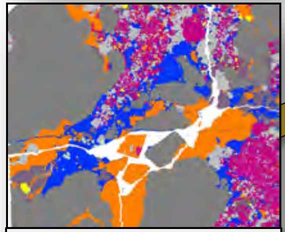
Target sulphide phases & characterise grain properties

*Hours*

**Buckwalter-Davis (2013)** Six tailings samples New Caloumet mine, Canada



XBSE



GXMAP

Characterise grain properties for mineral of interest and examine associations

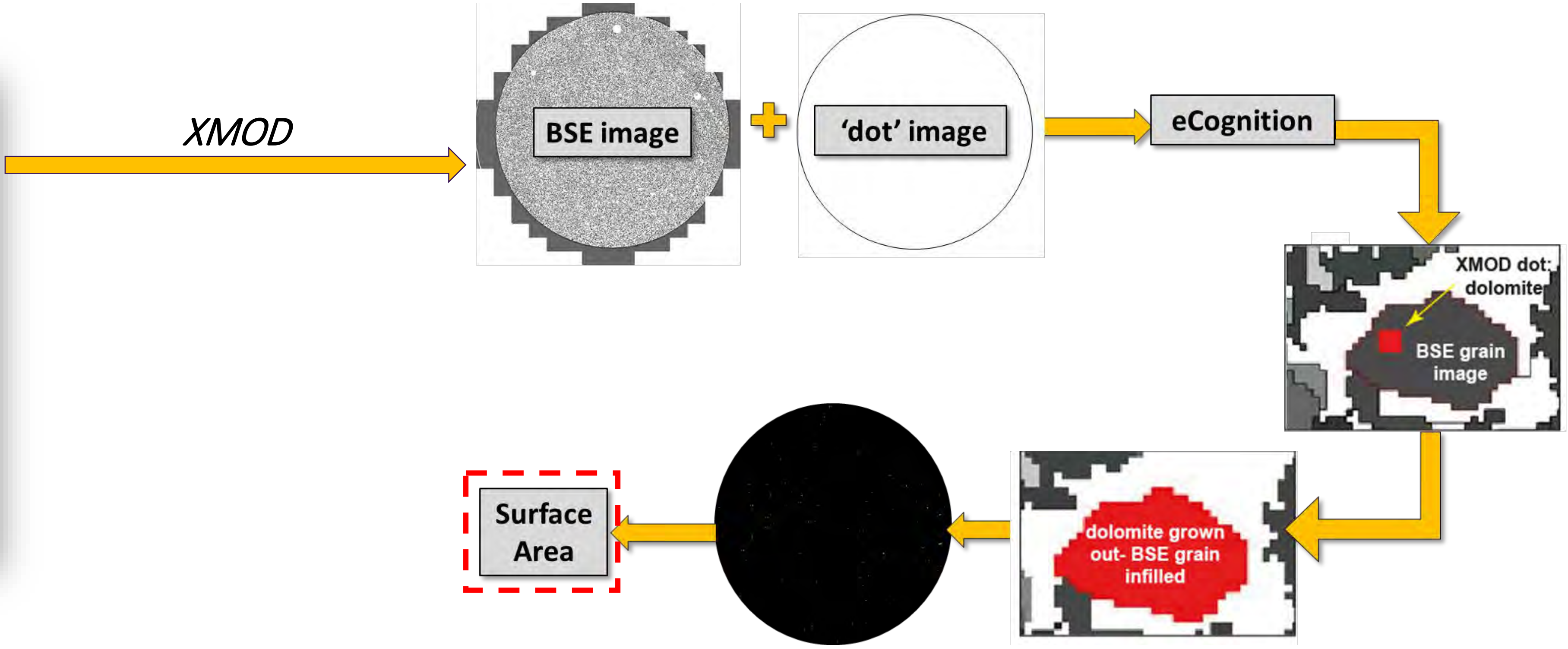
*Hours*

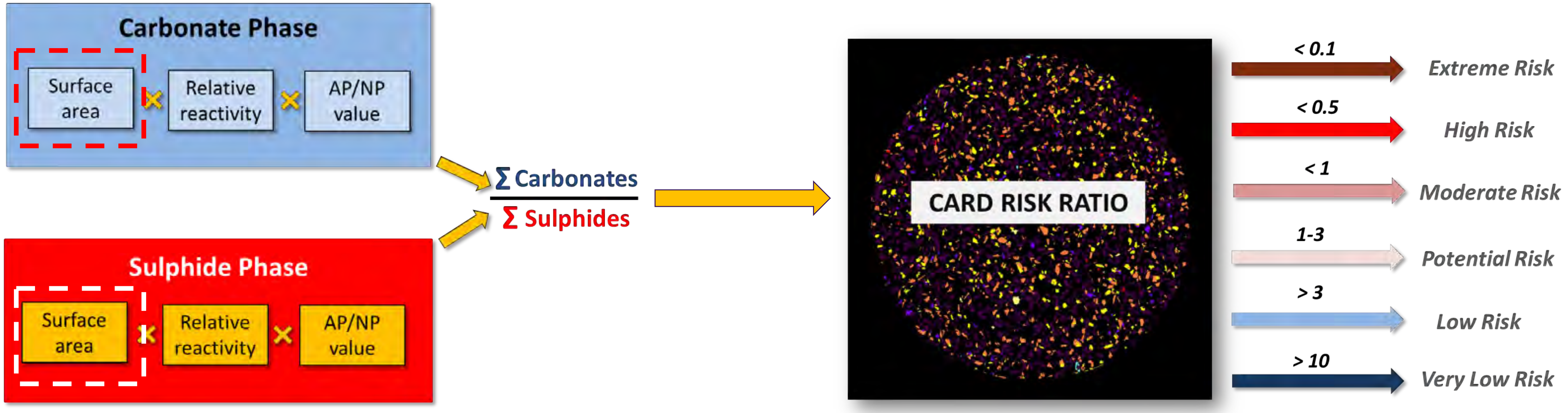
**Aranta (2010)**: 4 waste rock samples, Antamina Mine, Peru
**Parbhakar-Fox (2012):** 10 waste rock samples, Lode-Au mine, 9 IOCG samples, Australia
**Edraki et al. (2014)**: Cu-Au porphyry tailings

**Current practice:**
**Application in predictive ARD characterisation testwork and tailings characterisation**

**Commonly used techniques do not allow for low-cost high volume analysis- can XMOD be used?**

# Automated mineralogy

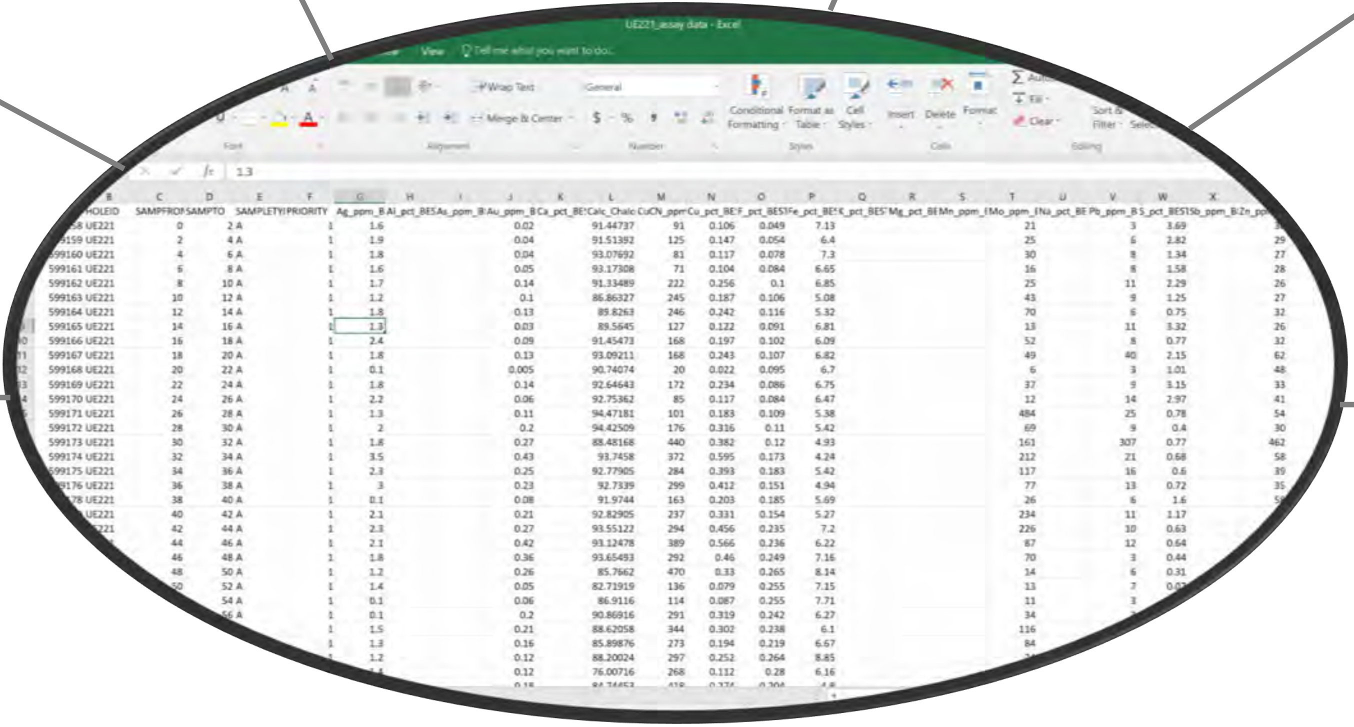




*Parbhakar-Fox et al. (2017)*

# Data mining and machine learning

The University of Queensland
AUSTRALIA

Matlab



SQL

Opportunity to enhance waste domaining e.g., using Ca and Mg from assay (Jackson et al., 2019)

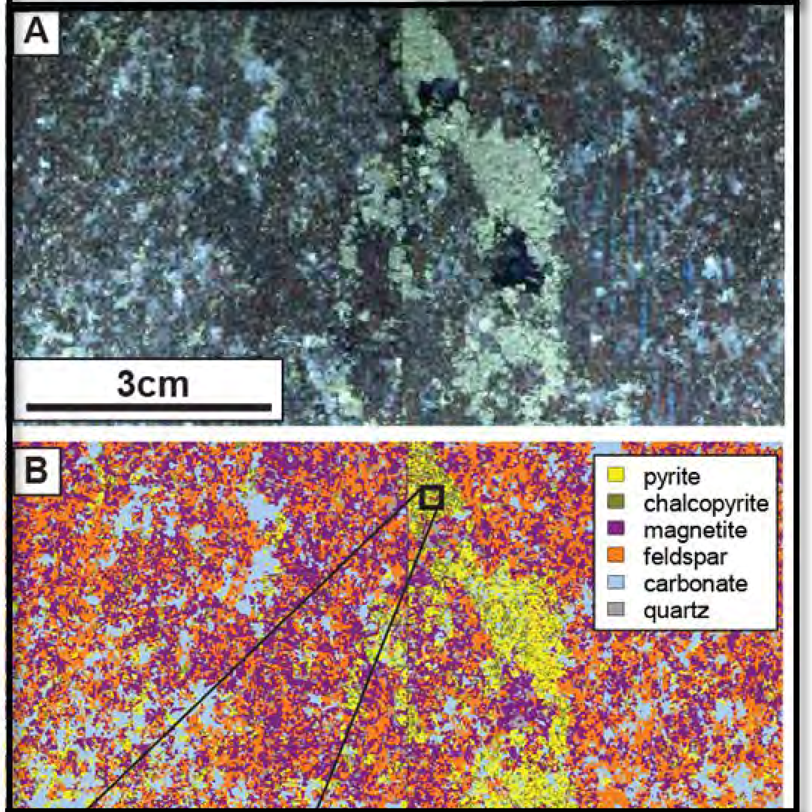
Extract more information from existing data sets e.g., mineralogy and texture (Cracknell et al., 2018)

Calculate mineralogy using assay data (e.g., Berry et al., 2015; Beavis et al. 2017; Howard et al., 2019)

# Data mining and machine learning



**High-res drill core image**




minerals
MDPI

*Article*

**Automated Acid Rock Drainage Indexing from Drill Core Imagery**

**Matthew J. Cracknell [1,2,*], Anita Parbhakar-Fox [1], Laura Jackson [1,2] and Ekaterina Savinova [3]**

1 Transforming the Mining Value Chain, ARC Industrial Transformation Hub, University of Tasmania, Private Bag 79, Hobart, TAS 7001, Australia; anita.parbhakar@utas.edu.au (A.P.-F.); lauraj0@utas.edu.au (L.J.)
2 Centre for Ore Deposit and Exploration Science (CODES), University of Tasmania, Private Bag 79, Hobart, TAS 7001, Australia
3 Corescan Pty Ltd., 1/127 Grandstand Road, Ascot, WA 6104, Australia; katerina.savinova@corescan.com.au

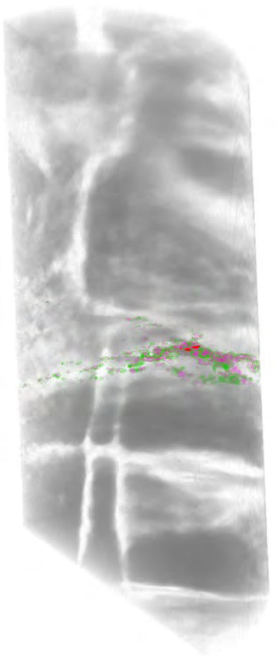
# ‘Next gen’ technologies



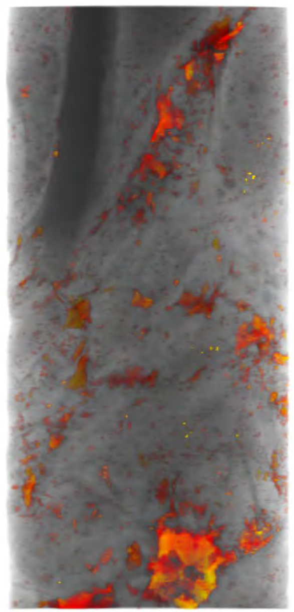

## X-ray tomography + XRF

Orexplore core scanning – structural features, ore and gangue phase morphology

*(200 µm voxel resolution)*



Sulphide distribution - Sunrise Dam



Pyrite – Rio Blanco tourmaline breccia Cu deposit

3D A-ARDI assessments


# Mine waste: Ore bodies of the future

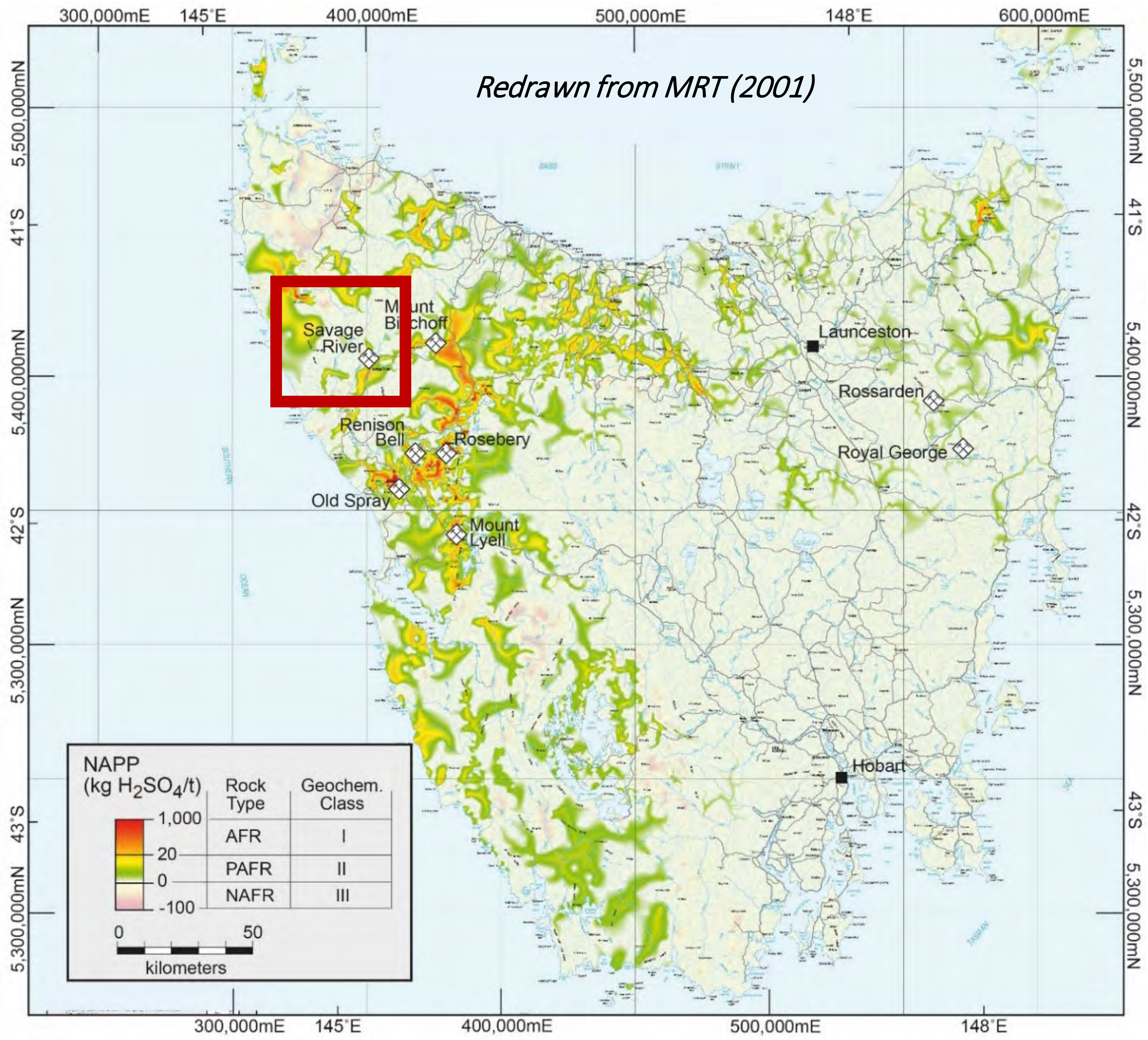


New cobalt resources

Tin and gold from historic tailings

Zinc from slag

New indium resources?




MMG

GRANGE RESOURCES

METALS X LIMITED

vedanta transforming elements

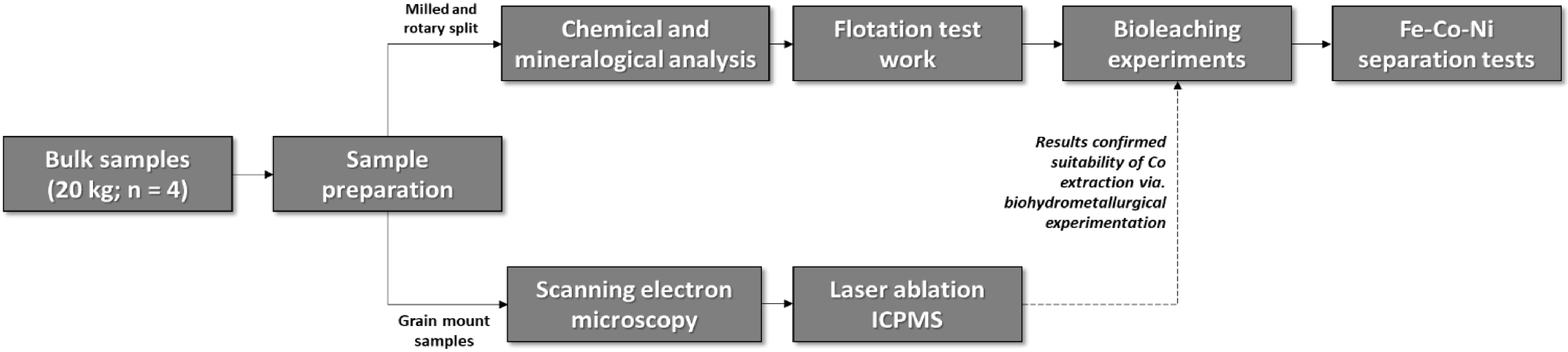
ELEMENTOS LIMITED

nq minerals

TARTANA RESOURCES LIMITED

# Mine waste: Ore bodies of the future

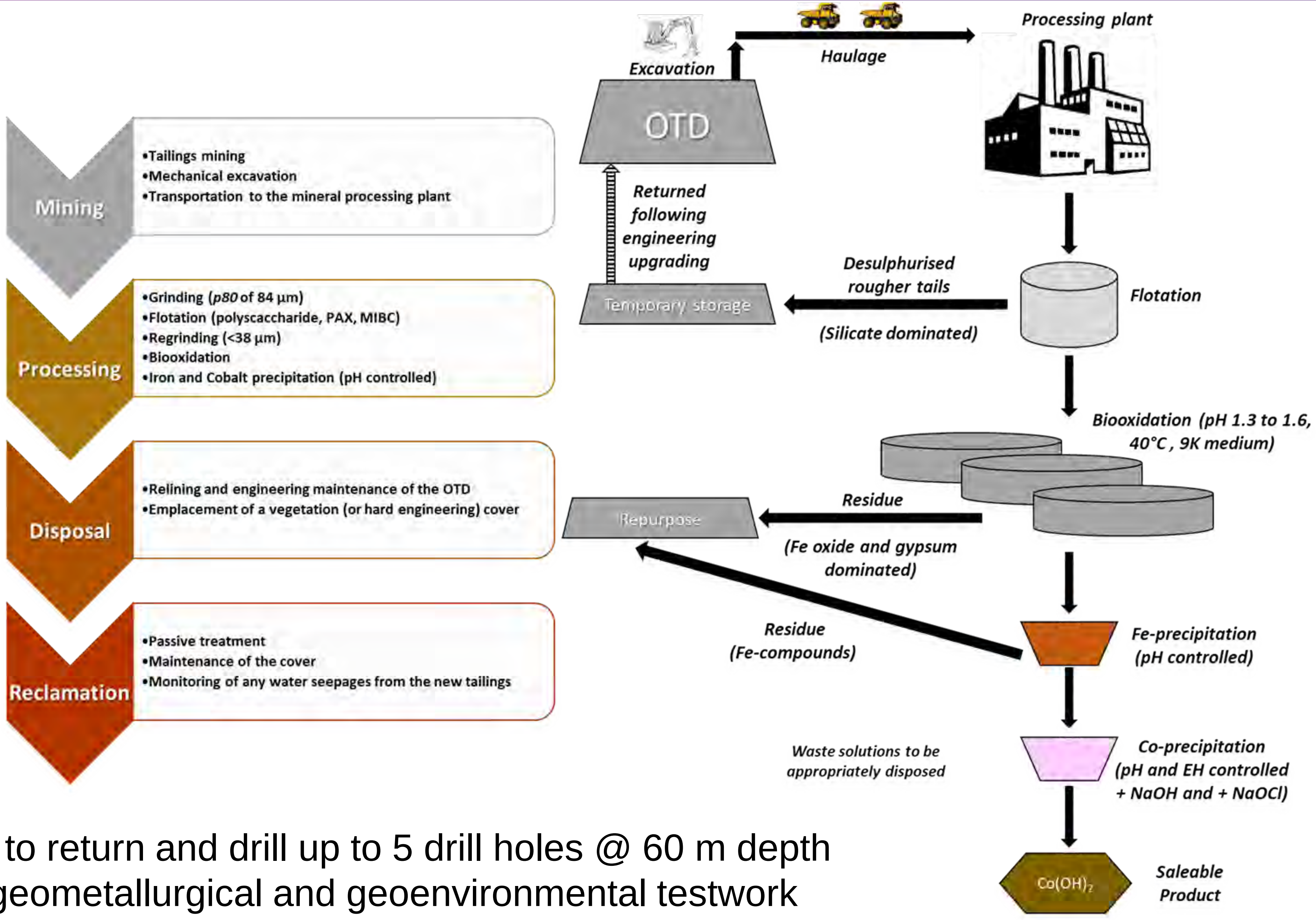





Parbhakar-Fox et al. (2018): https://www.mdpi.com/2075-163X/8/10/454

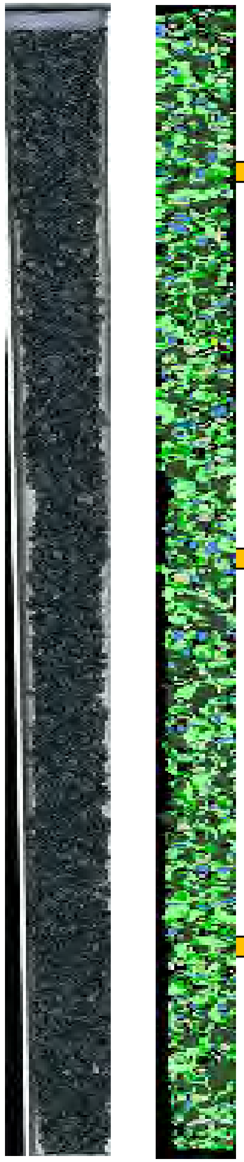
# Mine waste: Ore bodies of the future






Planning to return and drill up to 5 drill holes @ 60 m depth perform geometallurgical and geoenvironmental testwork

# Additional uses of geometallurgy data and tools



Forecast the potential for future mine wastes to fix atmospheric $CO_2$ (using TIR data): Develop GHG consumption index

Identify 'soft' zones based on classified mineralogy: Predictive dust characterisation protocol

Spent heap leach materials: identify and characterise post-leach mineralogy (e.g., alunite-group)

*Spent heap leach pile, Croydon Au-mines, QLD*

# ‘Enviro’ opportunities in geometallurgy

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“Transform how explorers and miners plan and predict mining and environmental activities, by providing new tools to guide these activities from the initial discovery through to end of mine life”

Mineralogical & chemical data analysis to predict AMD characteristics

‘Next gen’ technologies and new chemical testing

Sensor-based waste assessments during operational stages

Tailings ‘fingerprinting’ during deposition

Characterisation of historic mine sites and waste to determine reuse

New assessment tools and processing approaches

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# Thank you


Sustainable Minerals Institute
University Experimental Mine
40 Isles Road, Indooroopilly, QLD 4068

T +61 7 3365 5977 M +61 400 850831
E a.parbhakarfox@uq.edu.au

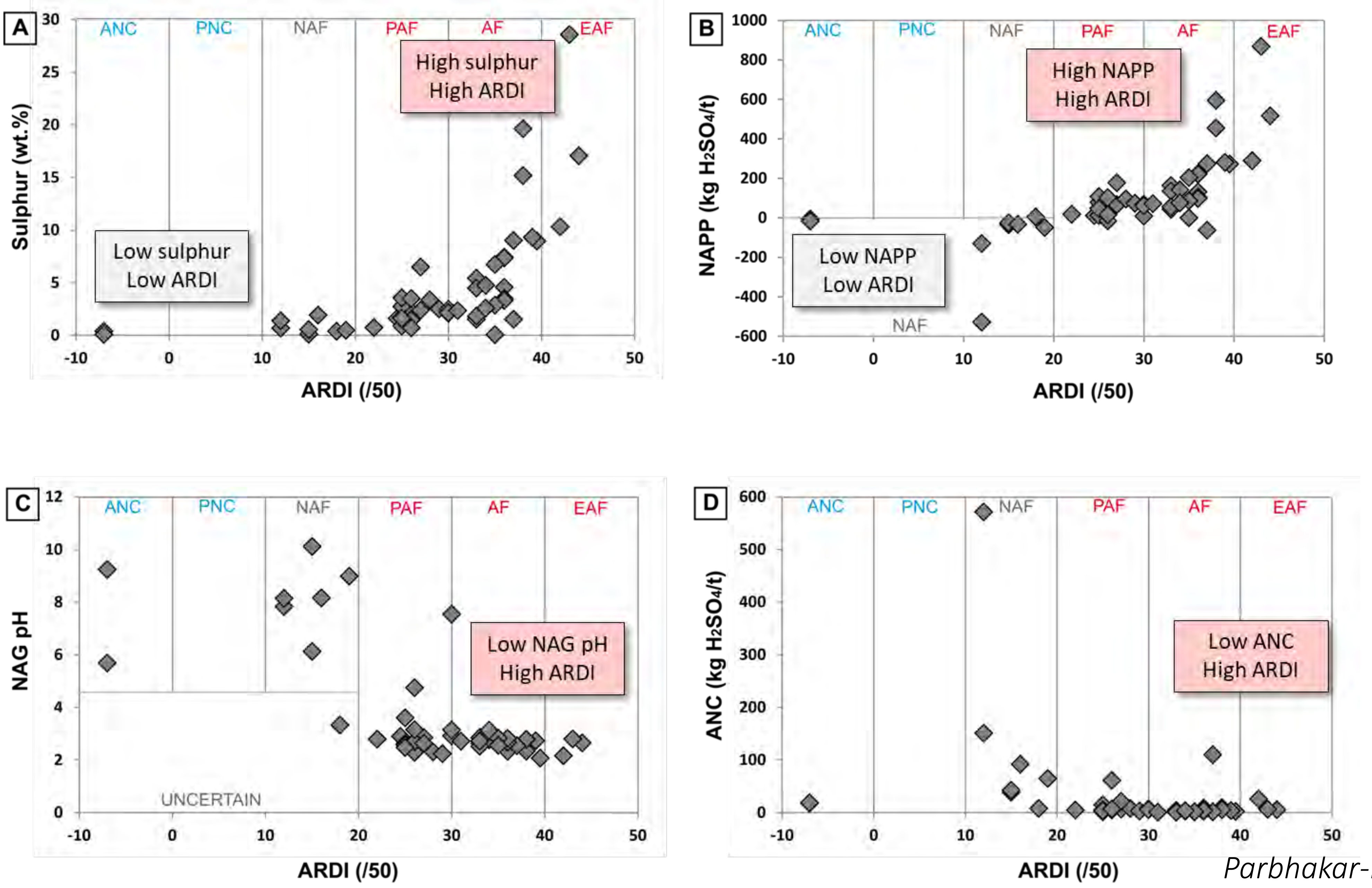

# What is ‘geometallurgy’?

- Through an integrated approach geometallurgy establishes 3D models which enable NPV optimisation and effective orebody management, while minimising technical and operational risk to ultimately provide more resilient operations
- Critically, through spatial identification of variability, it allows the development of strategies to mitigate the risks related to variability (e.g., collect additional data, revise the mine plan, adapt or change the process strategy, or engineer flexibility into the system)
- To achieve these goals, development of innovative technologies and approaches along the entire mine value chain are being established
- Geometallurgy has been shown to intensify collaboration among operational stakeholders, creating an environment for sharing orebody knowledge, leading to the integration of such data and knowledge into mine planning and scheduling
- Companies that embrace the geometallurgical approach will benefit from increased net present value and shareholder value

*Dominy et al. (2018)*

# Handheld tools and chemical tests






*Parbhakar-Fox et al. (2015)*

# INAP Workshop
# Evolution and Performance of Covers and Slope Treatment for PAF Waste Rock and Tailings
# 2 May 2019, SMI, UQ

*Professor David Williams*

*Director, Geotechnical Engineering Centre*

*Manager, Large Open Pit Project*

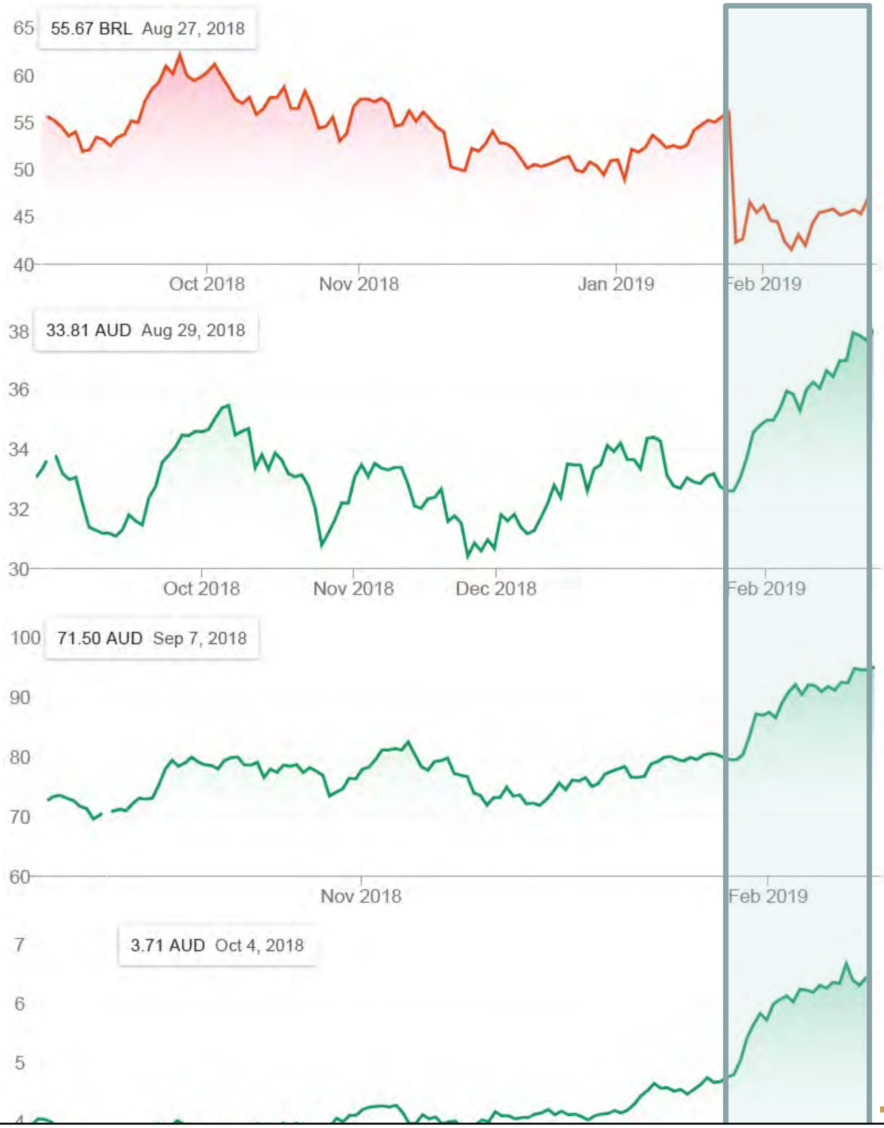
*The University of Queensland, Brisbane, Australia*

*Email: D.Williams@uq.edu.au*

# A Moment of Reflection

# Early Impact of Brumadinho Tailings Dam Failure on Share Prices

The University of Queensland
AUSTRALIA
Create change




Vale down initially 25.9%, recovering to 16.3% down

BHP up 15.1% since 25 January 2019

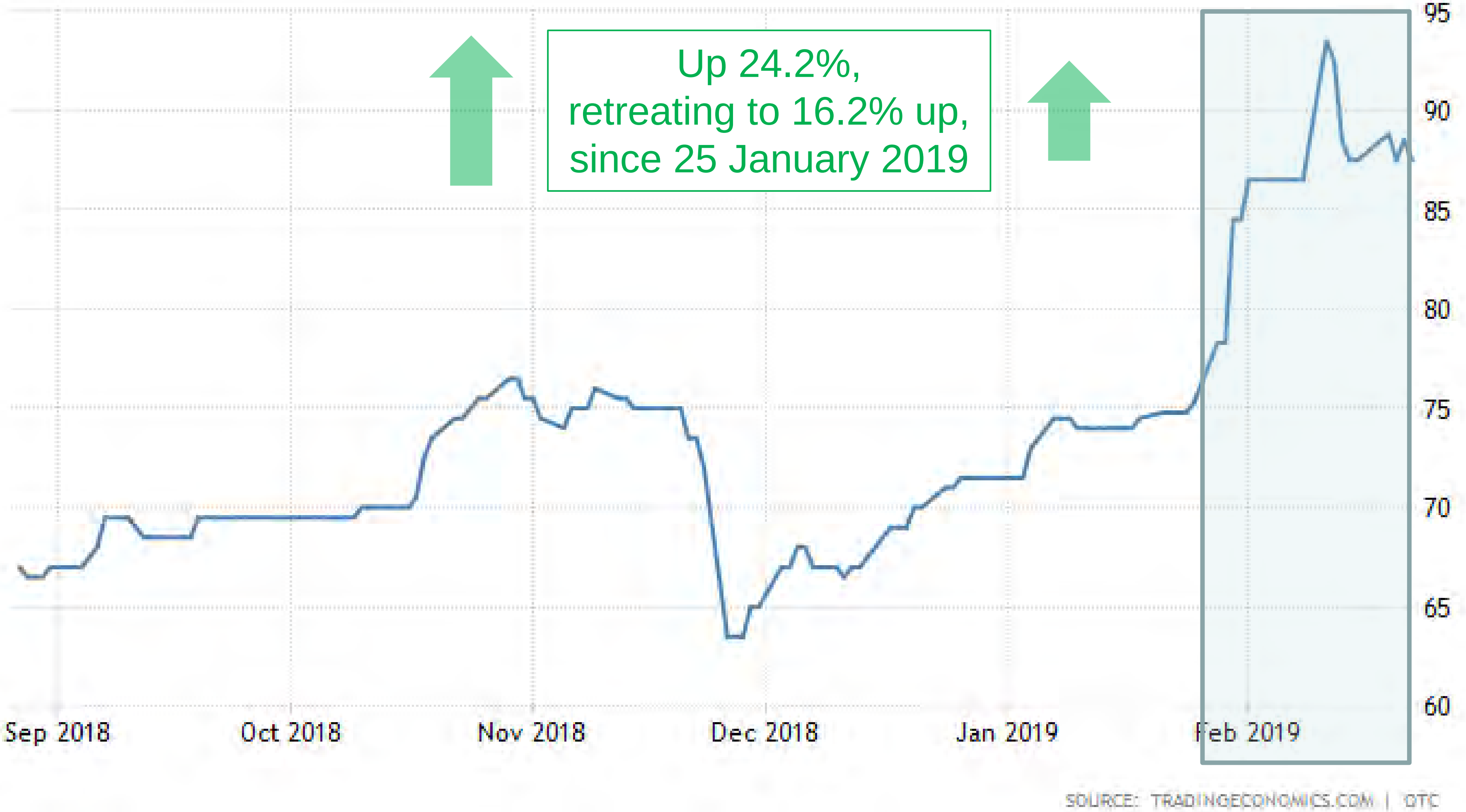
Rio Tinto up 18.2% since 25 January 2019

Fortescue up 34.4% since 25 January 2019

Market Capitalisation of all Iron Ore producers remained about same!

# Impact on Iron Ore Price (62% Fe in USD)





# Threats to Mining

- Pit failures can kill (less so now with monitoring), and impact operations
- Acid and Metalliferous Drainage (AMD) impacts streams and groundwater to perhaps 10s of km downstream, killing fish
- Tailings dam failures can kill (still) and impact infrastructure and environment up to 100s of km downstream
- Up to about 10 years ago, AMD was seen as key threat to mining → Covers
- Since then, tailings dam failures are key threat to mining – "Tail is wagging dog"! → Move away from slurry tailings

***All are threats to social and financial licences to operate***

# Evolution of Covers and Slope Treatment

- Covers:
  - Like “apple skins” – Prone to piercing and going “brown”
  - Initially limited in thickness, primarily to support revegetation
  - An increase in cover thickness was seen as an “improvement”
  - “Store and release” covers gained popularity for dry climates, but have not always been well designed and constructed
  - A composite cover is seen by Regulators to be “better”, and by Operators to be more costly.
- Slope treatment:
  - Predicated by a perception that grazing, and hence flattened slopes, is desired post-mining
  - Safe use of equipment on slopes requires flatter than 3H:1V
  - Flattened, topsoiled slopes “fail” in dry climates, as do drains
  - Must keep PAF wastes under flat top, not under slopes

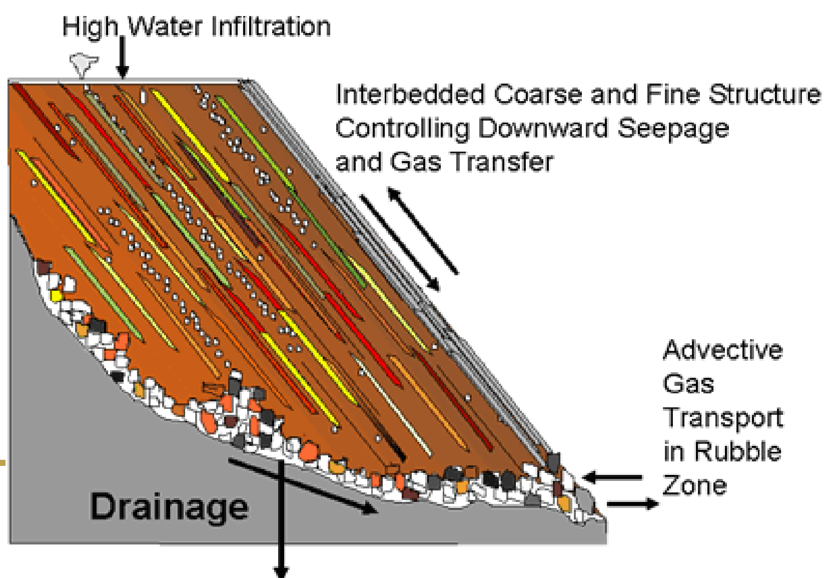
# Handling Acid and Metalliferous Drainage (AMD)

- Broadened to include neutral drainage, including elevated sulphates as at Macraes
- Identify, segregate and encapsulate sulphidic waste
- Limit exposure of sulphides – Progressive covering
- Release mine-affected water during high stream flows
- Covers were seen as silver bullet, but:
  - Covers are like an apple skin – Too thin and susceptible to failure
  - Shedding (wet climate) covers – Tend to fail due to erosion, particularly on slopes, requiring good vegetation and/or rock cover
  - Store and release (dry climate) top covers – Tend to fail due to unsuitable materials, poor design and construction, lack of a sealing layer, inadequate vegetation, etc.
- Perpetual water treatment is an undesirable last resort

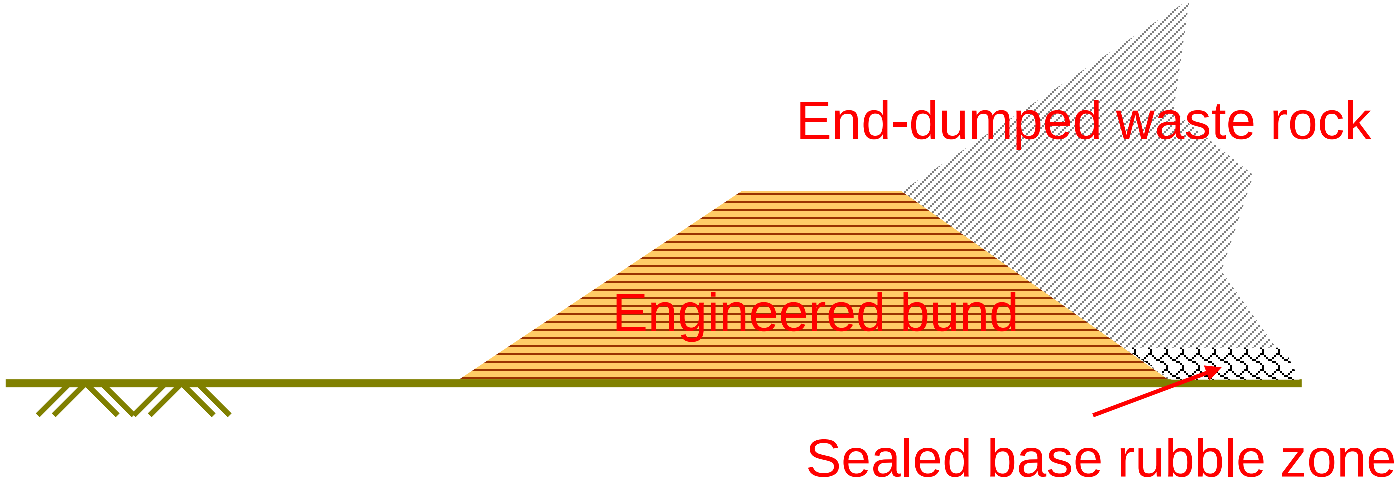
# Conventional Waste Rock Dumps

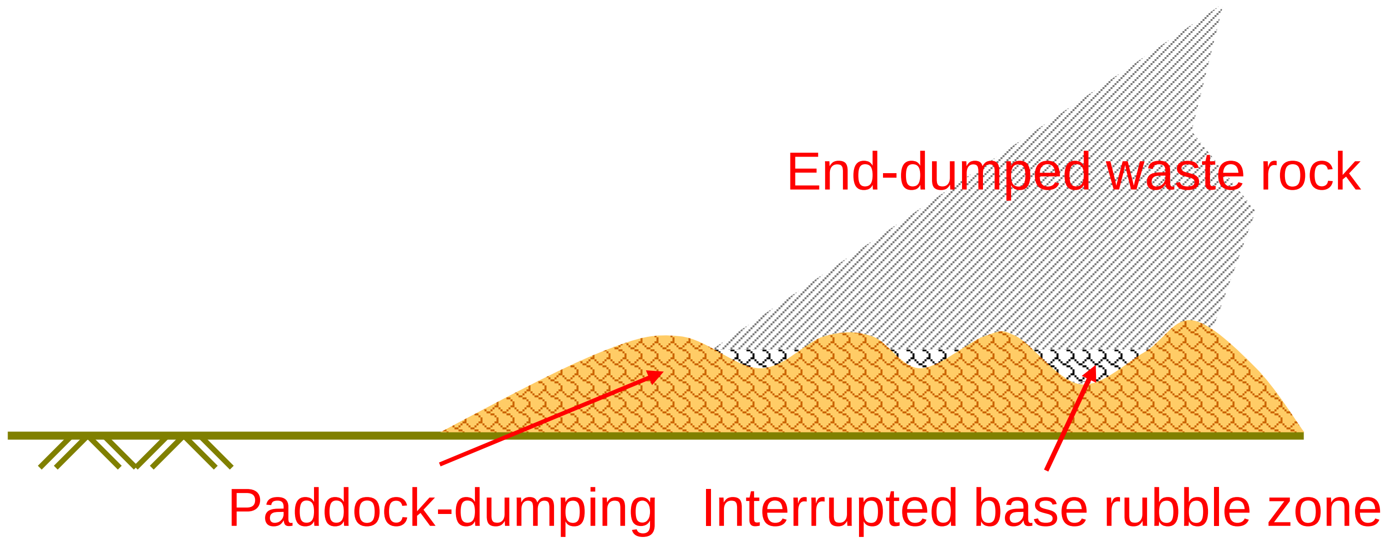
- Conventional approach of dumping waste rock as close as possible to pit, then pushing out until it is cheaper to go up, inverts ground profile, exposing potentially contaminating waste rock on top and far side of dump:


- Conventional practice of end-dumping waste rock produces “oxidation reactors”:



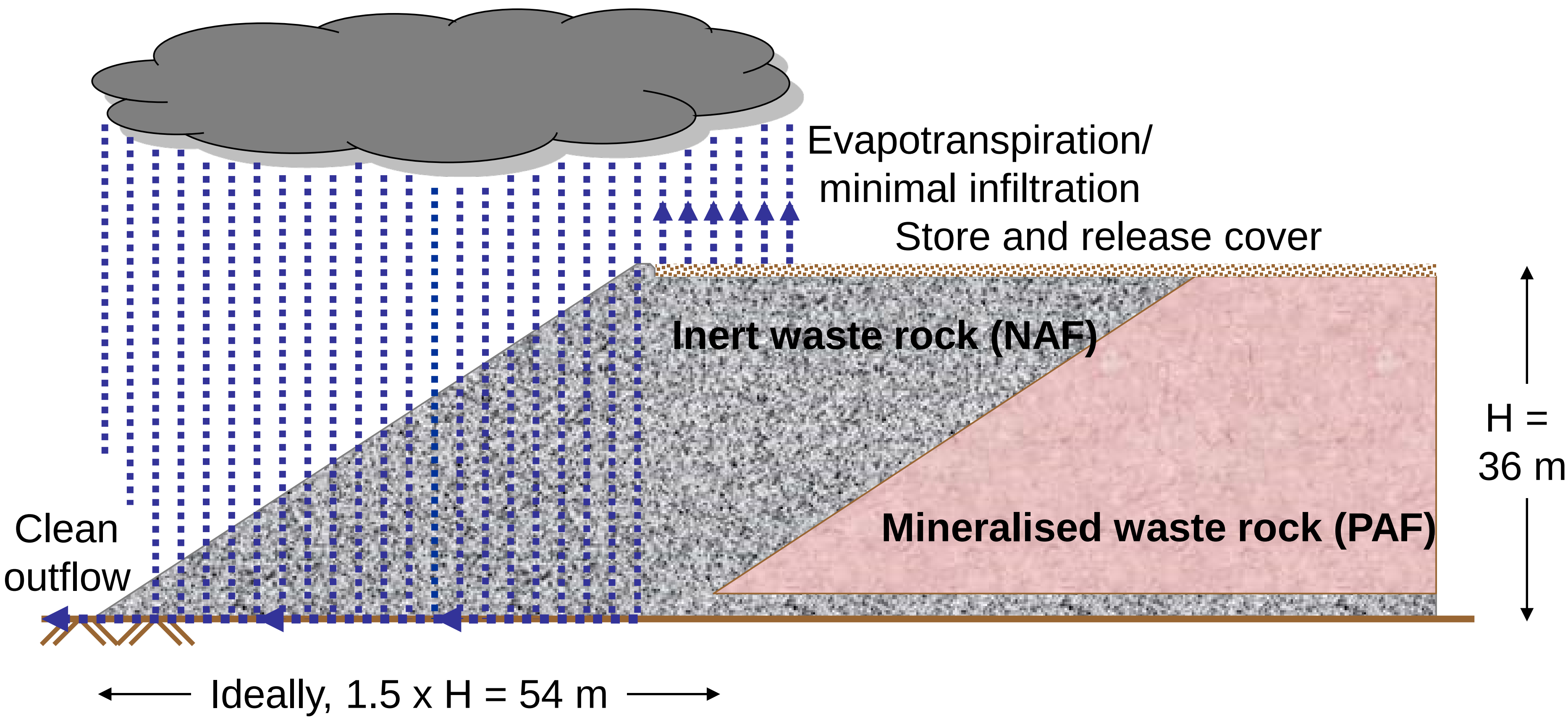
# Low Permeability WRD Toe



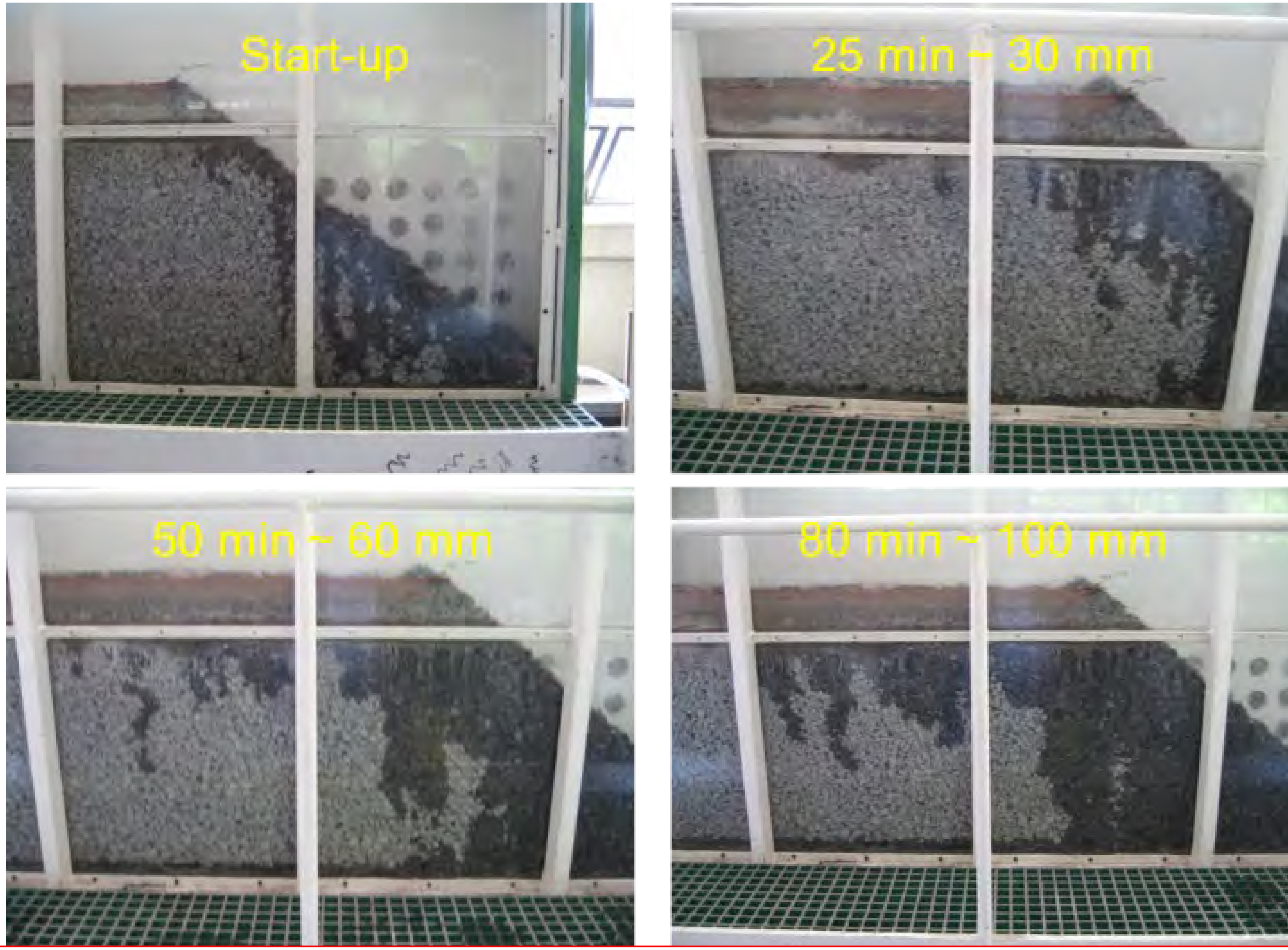
# Encapsulation of PAF Waste Rock – Kidston





# Wetting-Up Waste Rock Dump

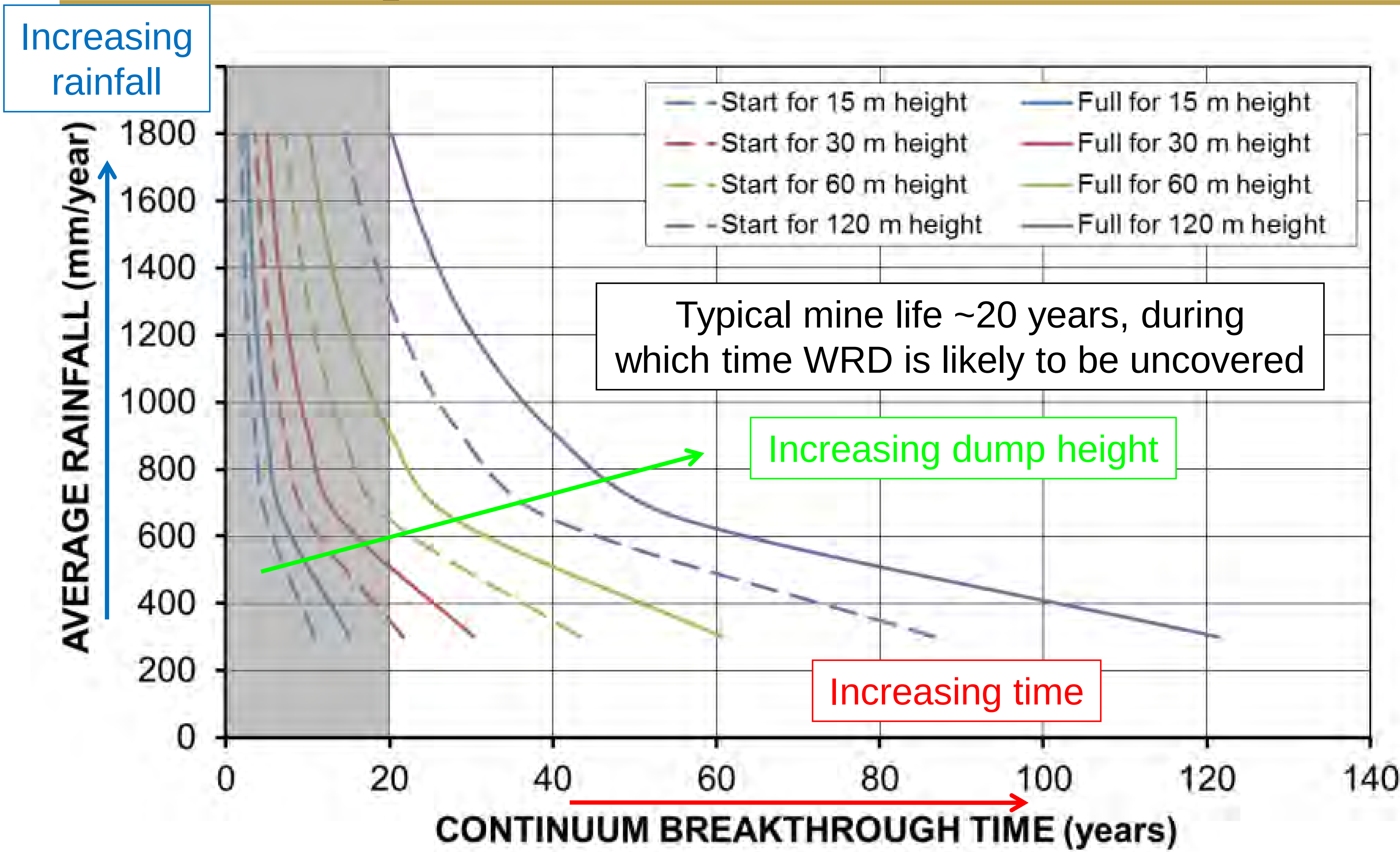





Weathered waste rock will flow once ~60% saturation is reached
Durable waste rock will flow once ~25% saturation is reached

# Wetting-Up of Weathered Waste Rock Dumps

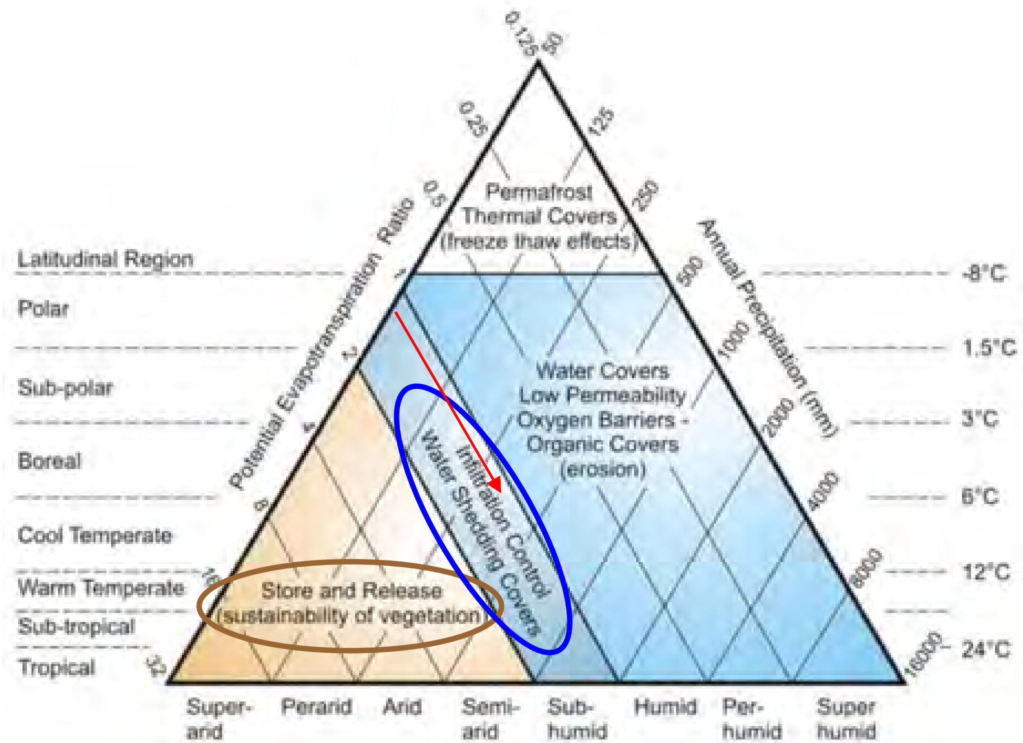




# Soil Cover Systems as a Function of Climate (GARD, 2009)

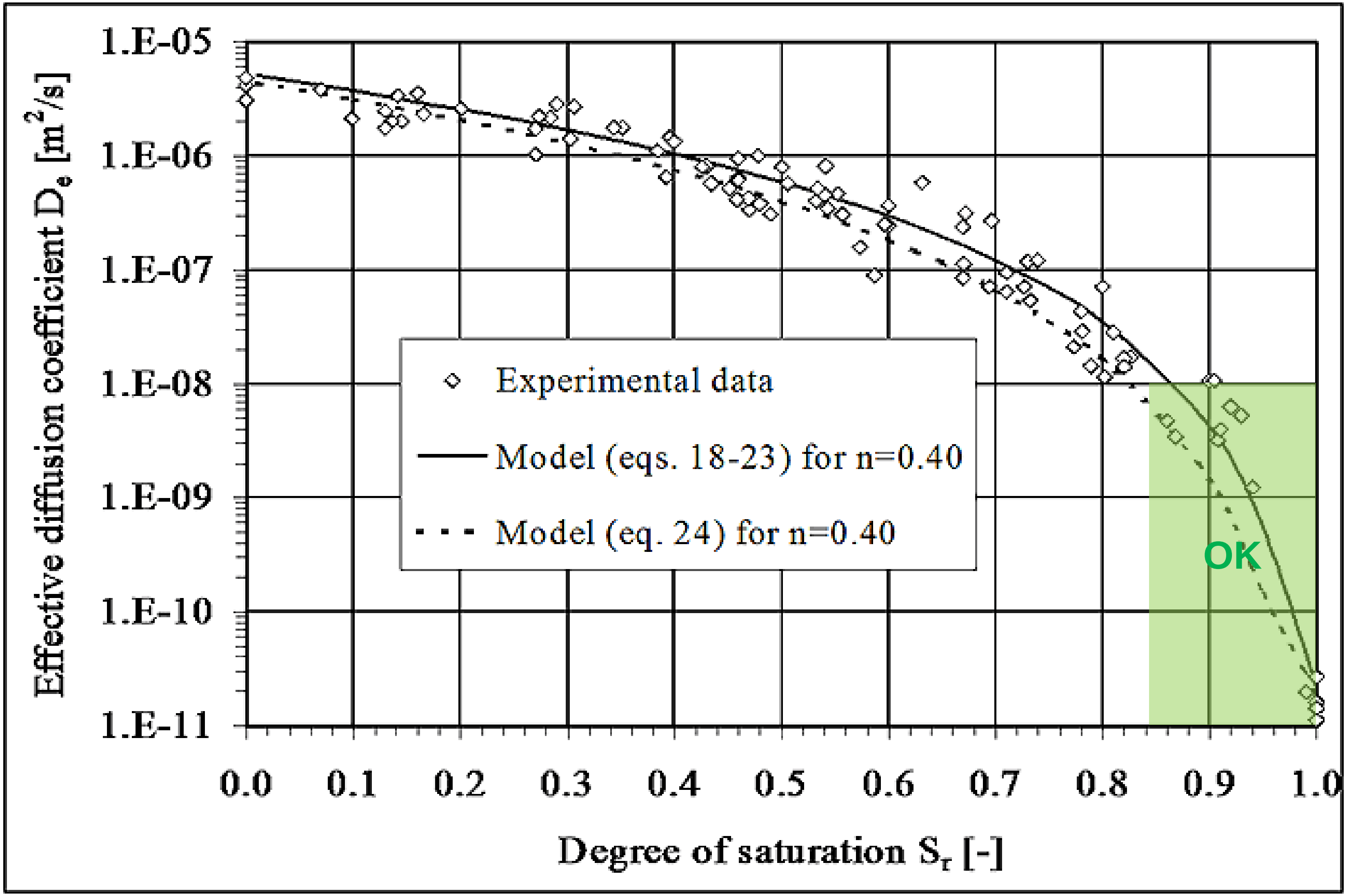


- Soil cover systems for dump tops are intended to limit oxygen ingress and net percolation
- Two most common soil cover types are:
  - Rainfall-shedding or barrier covers, better-suited to **wet** climates **– Appropriate for Macraes**
  - Store and release covers, better-suited to **dry** climates

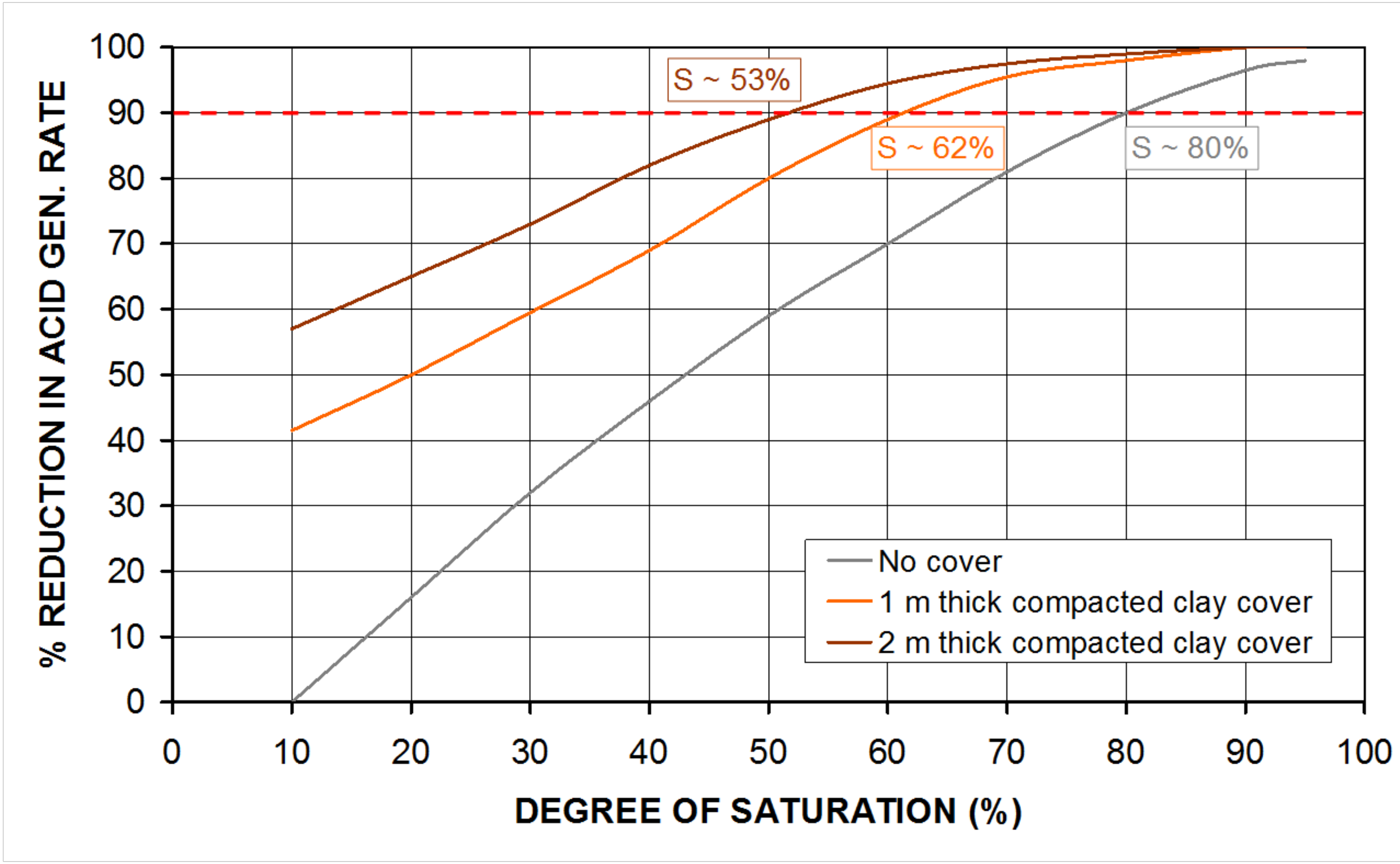



GARD (2009)

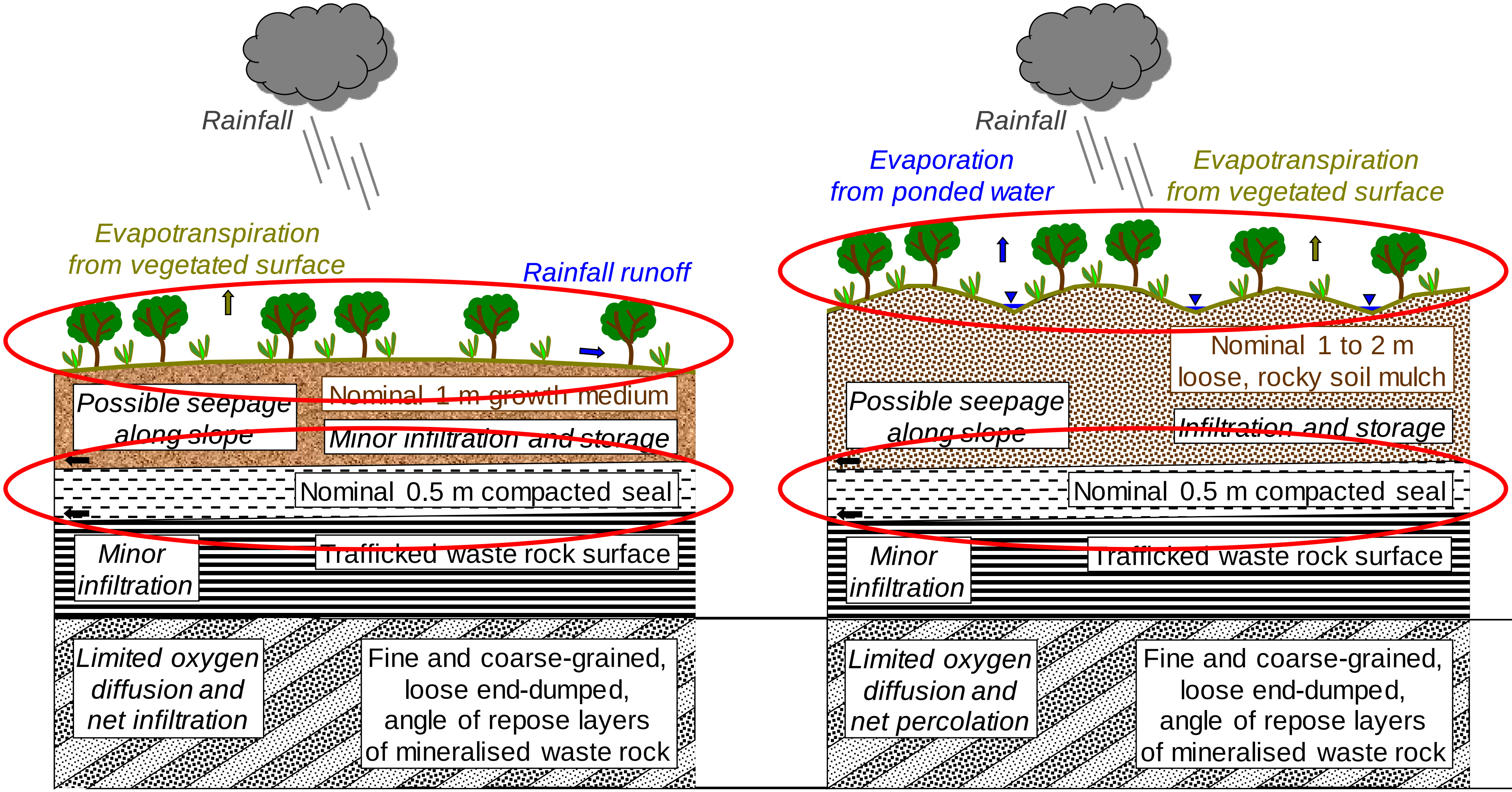
# Oxygen Diffusion Rate vs. Degree of Saturation (GARD, 2009)



# Oxygen Ingress = Fn (Compacted Clay Cover Thickness) (EGi, 2000)



# Conventional Covers over Dump Tops



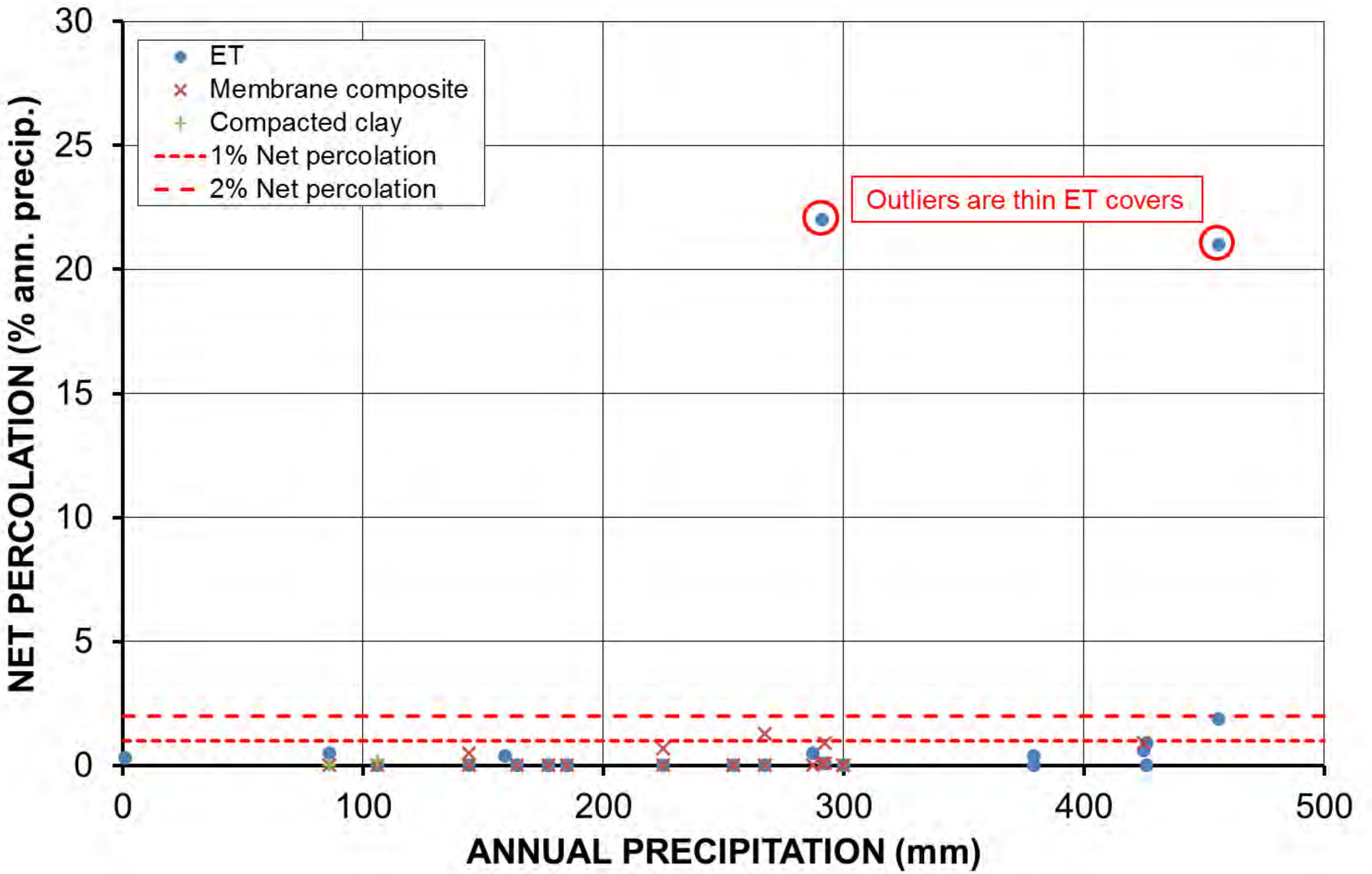

Rainfall-shedding – **WET** climates

Store and release – **DRY** climates

# Cover System Performance (USEPA, 2011)

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

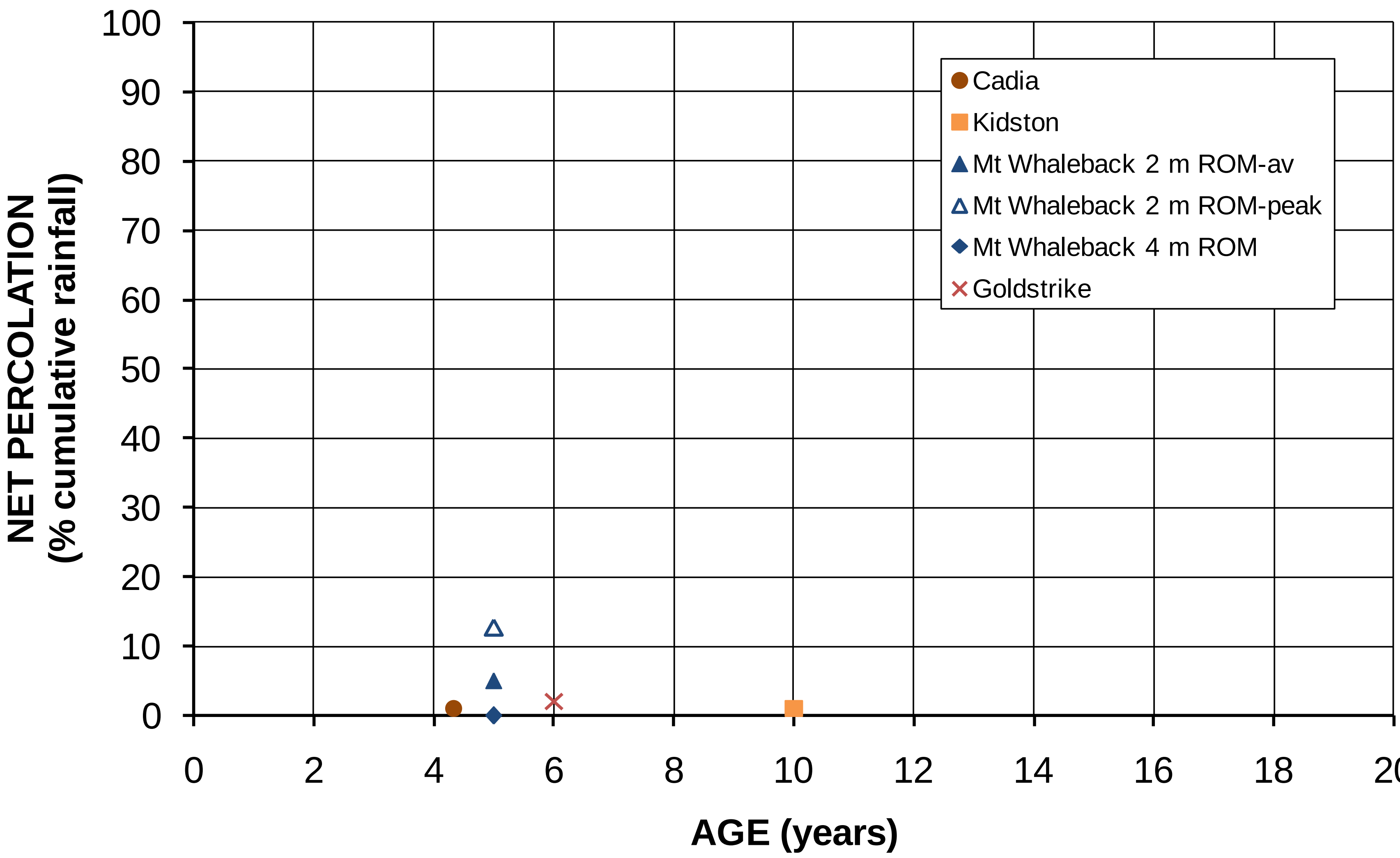
Create change



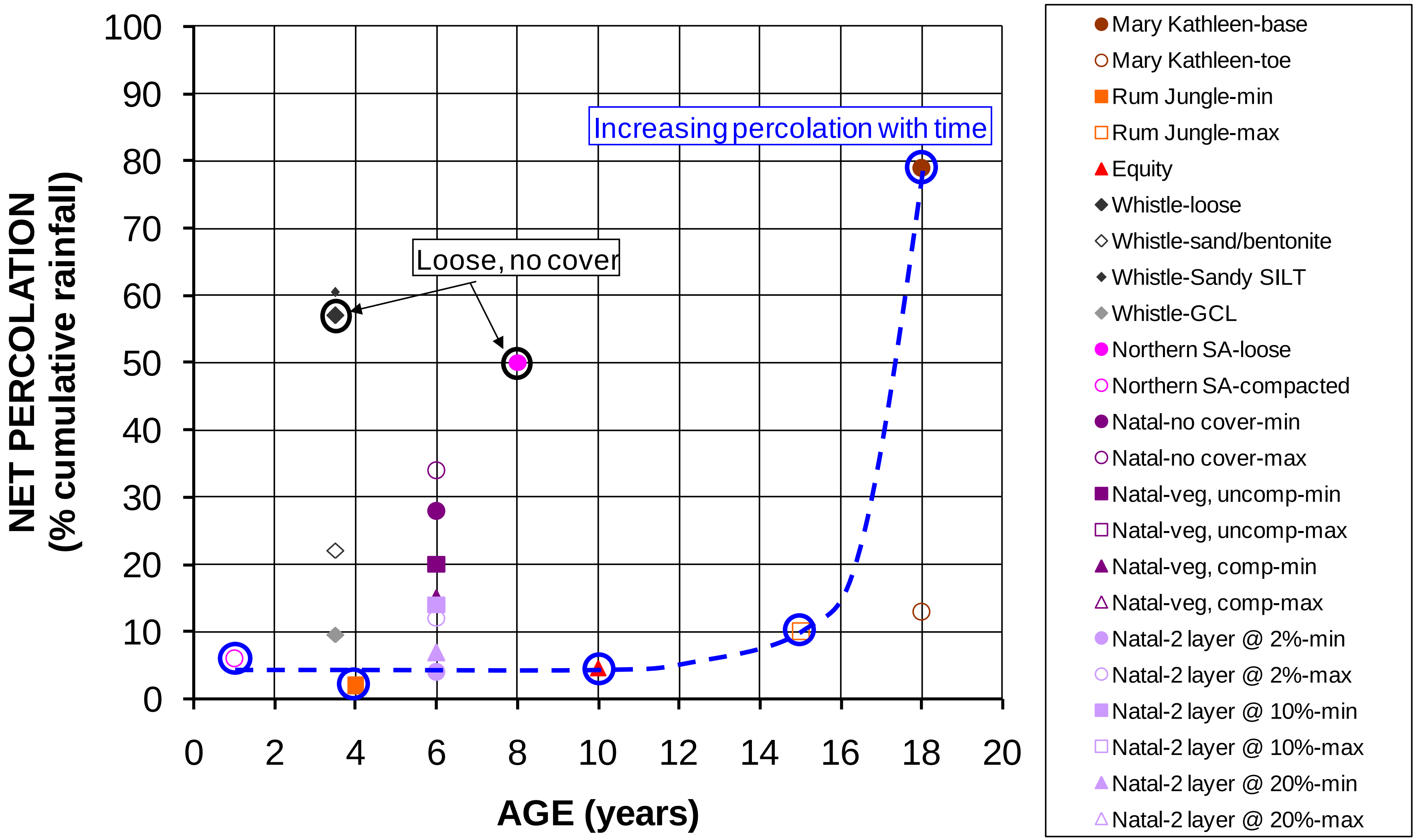

Well-designed and constructed covers generally limit net percolation to <2% of annual precipitation in dry climates

# Store and Release Net Percolation



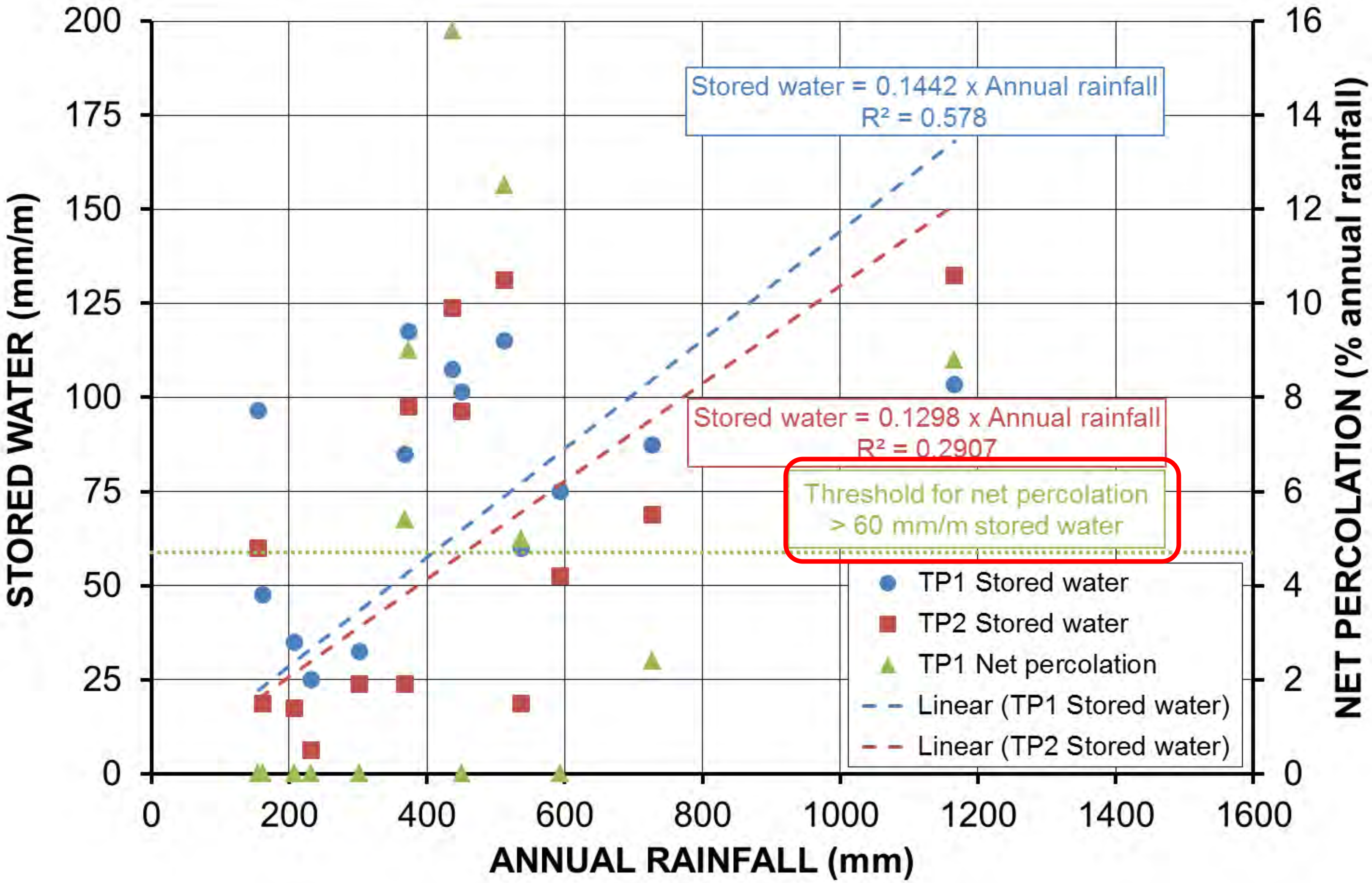


# Rainfall-Shedding Net Percolation



# Mt Whaleback 2 m & 4 m Thick Cover Performance (Bonstrom *et al.* 2012)






**Note:** A well-constructed store and release cover should store ~250 mm/m before percolating

# Performance of Covers on Dumps


# Over-Dumping of Fines on Angle of Repose WRD Slope and Revegetating


# Rock Covers on Flattened Mine Slopes

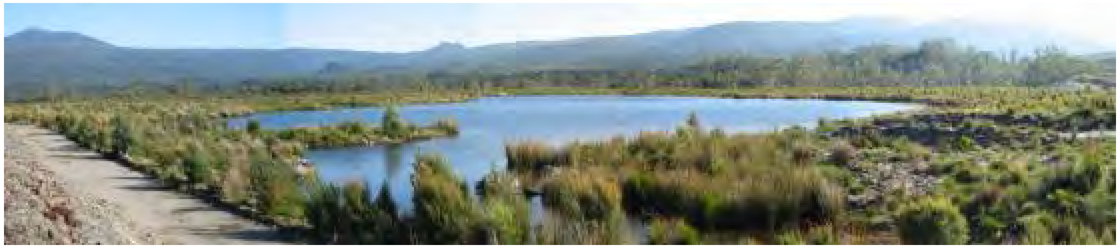

# WRD Toe Seepage – Failed Passive (SRB) Treatment – Kidston

# Conventional Slurry Tailings Disposal



- Tailings disposal has been based on minimising short-term capital and operating costs, with rehabilitation costs discounted by application of a High Discount Factor in an NPV approach to accounting
- This has led to widespread adoption of surface tailings storage facilities to store slurried tailings delivered by robust and cheap centrifugal pumps and pipelines
- Limited tailings dewatering, densification and strength gain results in a wet, low density, soft tailings deposit that occupies a large storage volume, requires frequent wall raises, and presents rehabilitation difficulties
- Whole-of-life costs of combined slurried tailings disposal, storage and rehabilitation are high

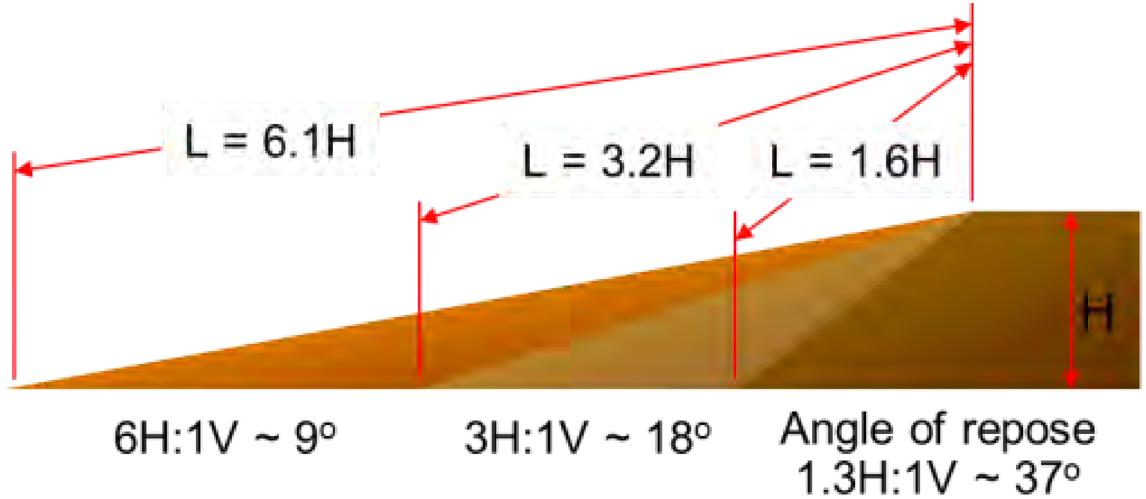
# TSF Perimeter Peat and Central Water Cover in Tasmania (Brett, 2011)



# Rationale for WRD Slope Reshaping

- Not required for:
  - Geotechnical slope stability
  - Erosional stability, in fact steep rocky slopes are more stable against erosion than flattened slopes, particularly if these are topsoiled
- May be required:
  - For safe access
  - To better match natural landforms and for cultural reasons
  - To facilitate vegetation

# Height H is Fixed, Slope Length L (AND Erosion) Increase with Dozing



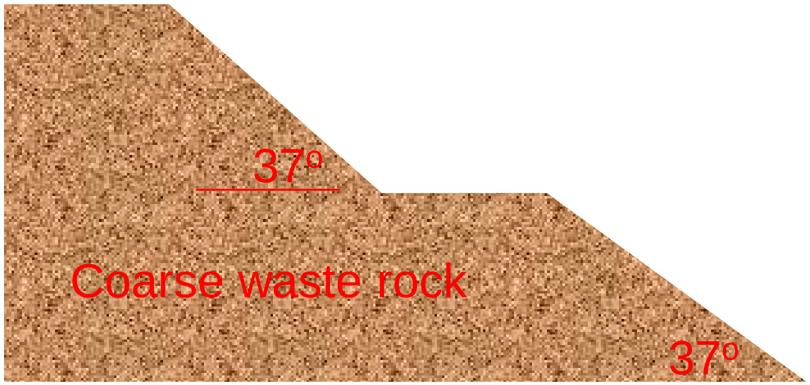

Increasing catchment on slope flattening

# Increased Erosion from Flattened Slope (25 mm Storm) – Kidston

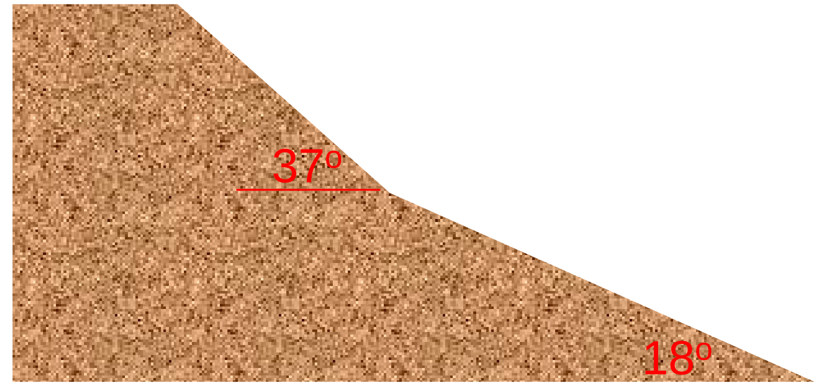


# Simply Constructed (Natural) Concave Slopes to Reduce Erosion



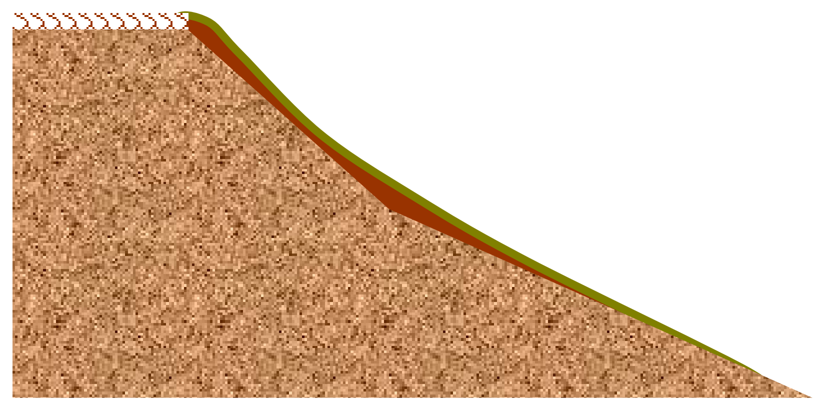



1. Benched stockpile slope




2. Lower bench dozed

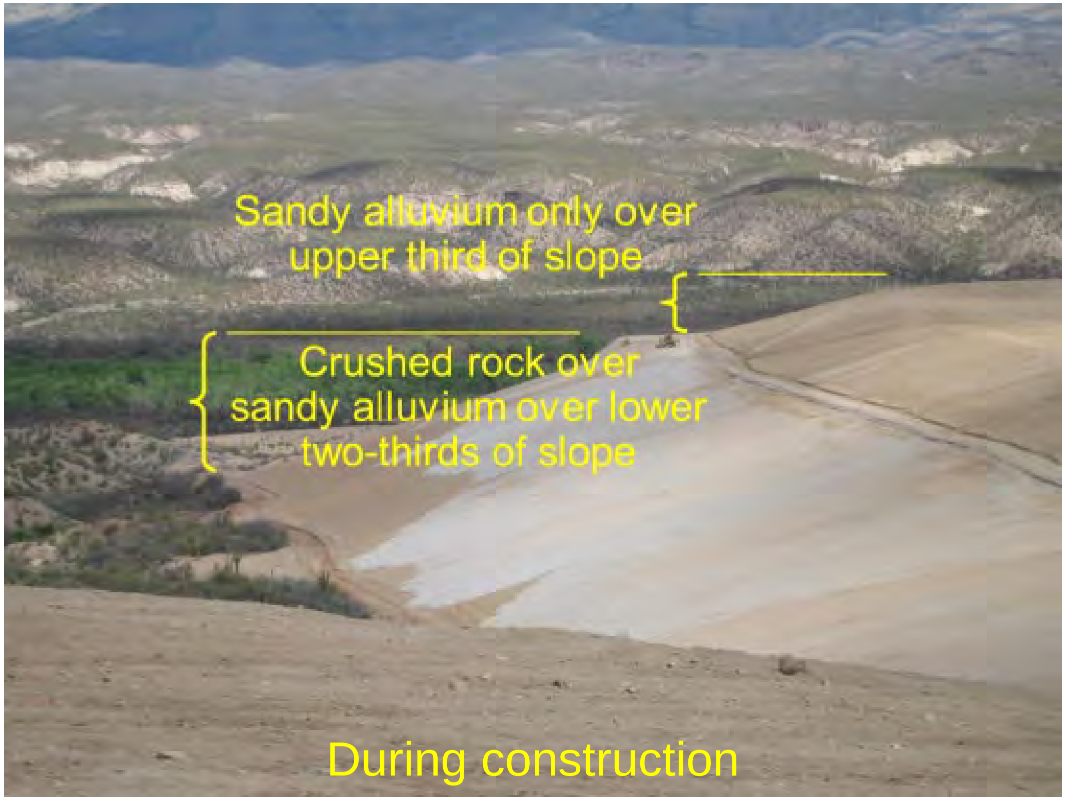

3. Over-dumping with fines



4. Vegetated concave slope

# Successful Rehabilitation of 100 m High TSF Slope – San Manuel, AZ







# Rock-Covered Heap Leach – San Manuel, AZ


A demonstration of pollution control from underground mines: Update on the Inert Atmosphere Technology

*Earth Systems Consulting Pty. Ltd.*

EARTH SYSTEMS
Environment | Water | Sustainability

# Pollution Legacy from Underground Mines

- There are hundreds of thousands of abandoned underground mines globally as this was the preferred mining method.
- Approximately 5-10% of current mines are underground operations.
- Few remediation techniques are available to manage ARD discharges from derelict underground mines.
- Existing techniques include:
  - Prevent ARD using pressure bulkheads / hydraulic adit seals and mine flooding.
  - Treat the ARD discharged in perpetuity (active or passive).

# The Behaviour of Mine Void Atmospheres

- For underground mines, stored sulfidic waste rock represents the largest source of ARD. Waste rock is backfilled to facilitate mining. Wallrock within a mine is predicted to be a relatively small contributor to site acidity loads.

$$FeS_2 + 3.75\,O_2 + 3.5\,H_2O = Fe(OH)_3 + 2\,H_2SO_4$$

*Pyrite + 0xygen (from air) + Water = ferrihydrite + Acidity (acid & metals)*

- Pollution in mine discharge can be measured: Flow Rate x Acidity = Pollution Load (tonnes $H_2SO_4$/unit time).
- Pyrite oxidation reaction quantifies the relationship between pollution generation and oxygen consumption within the voids.
- Example: 1,000 tonne of $H_2SO_4$ acidity (acid & metals) per year from an underground mine indicates:
  - ~610 tonnes of $FeS_2$ (equivalent) oxidised per year.
  - ~610 tonnes of oxygen [$O_2$] converted to sulfate per year.
  - ~430,000 $m^3$ of oxygen [$O_2$] gas from air per year, which is equivalent to ~2 million $m^3$ of air.

# The Behaviour of Mine Void Atmospheres

- Currently the key mechanism for oxygen resupply is via advection associated with free air movement and barometric pumping through key air entry pathways.
- Without air entry controls, there is effectively no limitation to oxygen resupply at most derelict mines (just like waste rock piles).
- Every 1.0 $m^3$ of oxygen consumed within a mine void is replaced by 1.0 $m^3$ of air, that contains only ~21 vol.% $O_2$.
- By careful control of air entry, nitrogen enrichment (via sulfide oxidation) within voids is unavoidable (just like in TSFs and well constructed waste rockpiles).
- The key to limiting acidity generation (pollution) is to slow the resupply of $O_2$ to less than the rate of sulfide oxidation. This condition will ensure passive nitrogen enrichment.
- The key to preventing acidity generation (pollution) is to prevent the resupply of $O_2$.

# Inert Atmosphere Technology

Inert Atmosphere Installations are broadly a two stage process.

STAGE 1:

- Careful assessment of mine workings (Feasibility Study).
- Design & construction of strategic air-entry and drainage controls.
- Installation of Monitoring equipment (next slide).
- Internal sulfidic waste rock will passively consume oxygen.
- When sulfide oxidation rate exceeds oxygen re-supply, pollution generation is lowered.

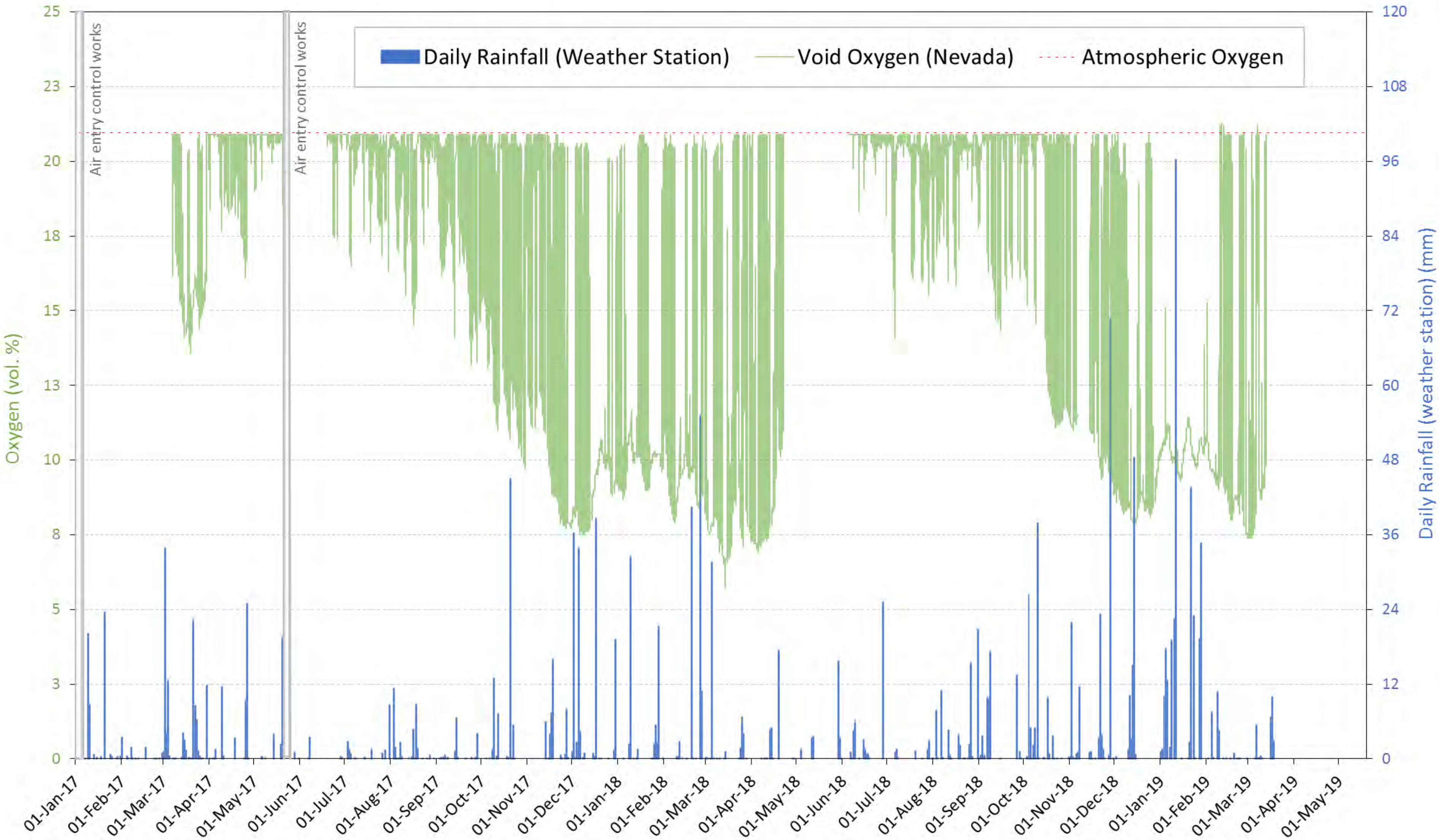
STAGE 2:

- Controlled injection of small quantities of inert gas (eg. nitrogen, carbon dioxide or mixtures) to compensate for any residual barometric pumping or residual air-entry. This can avoid any air resupply and prevent water quality impacts (not possible with waste rock piles).

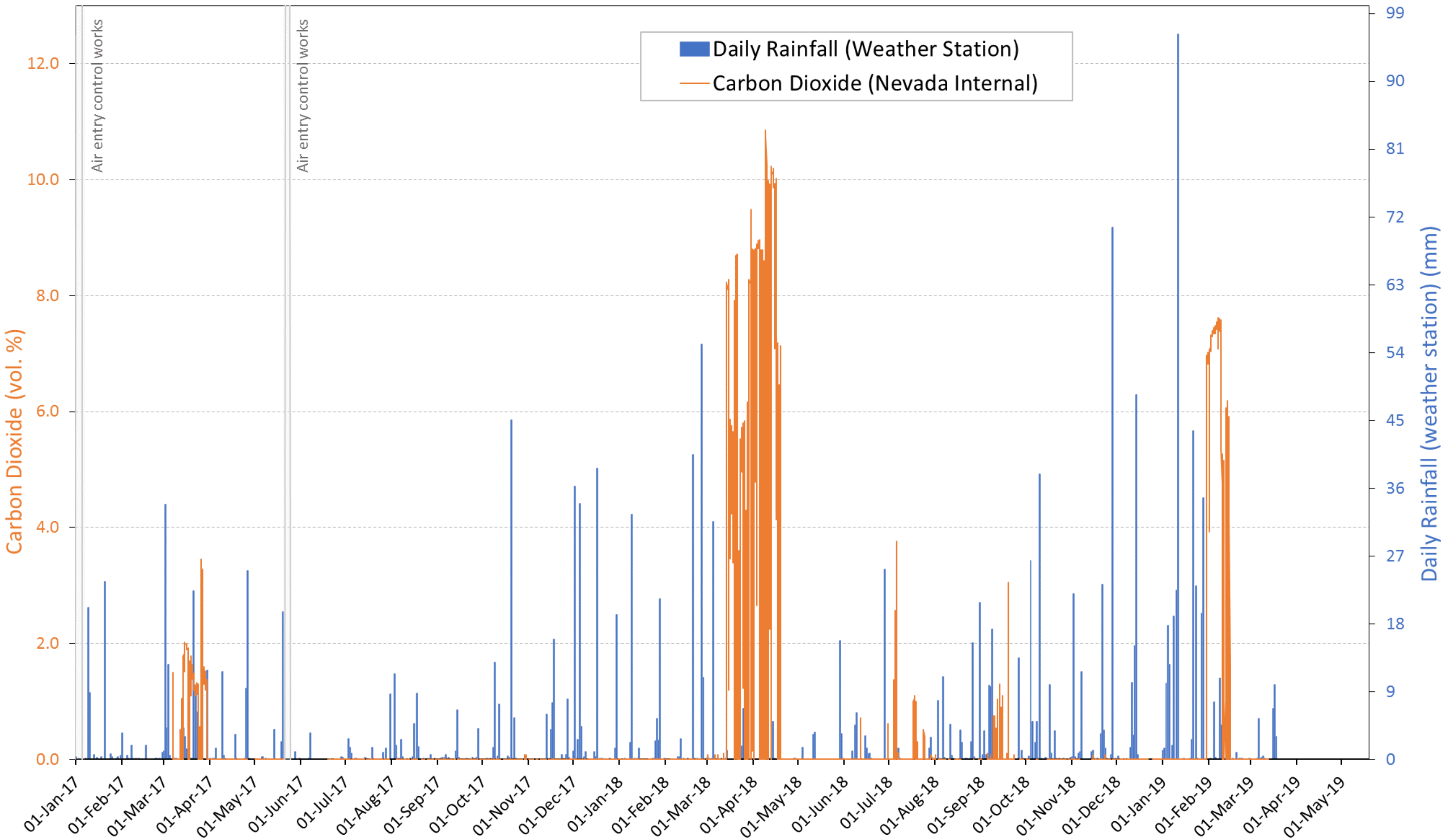
# Case Study: Nevada

- Nevada mine is a small historic gold mine located in Central Eastern New South Wales, Australia. Mining dates back to the mid-1800's. Three adits, three shafts and a stope to surface.
- Low pH, high sulfate discharge from a single adit. Acidity loads of 3-5 tonnes $H_2SO_4$ per year. Discharge contains elevated iron, aluminium, zinc, copper, lead, cadmium, nickel and sulfate.
- Inert atmosphere installation January 2017.

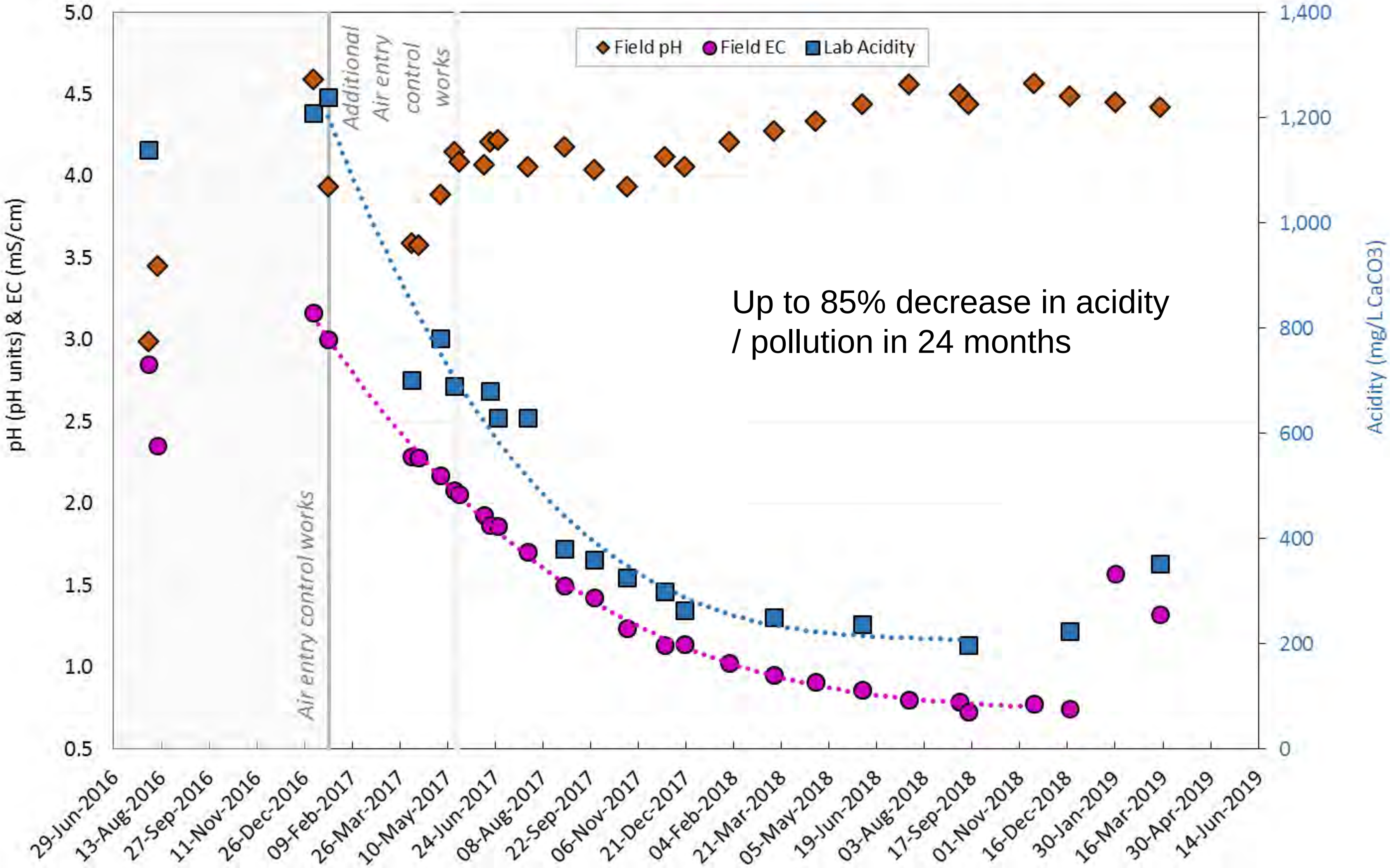
# Void Oxygen & Rainfall

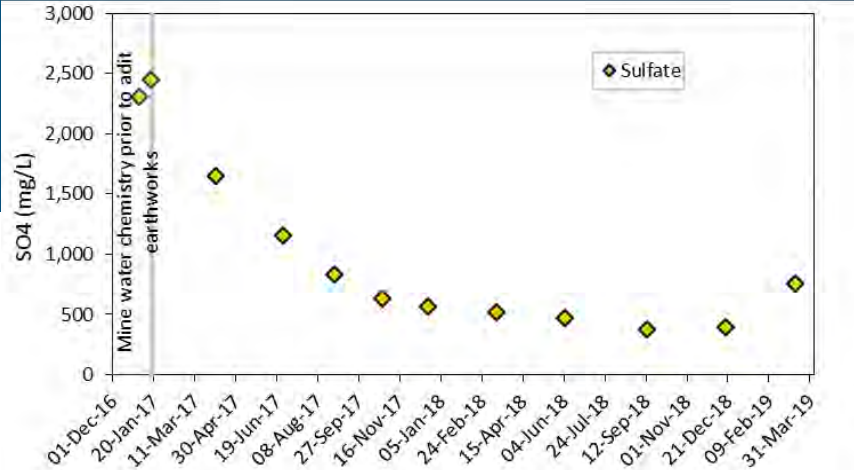


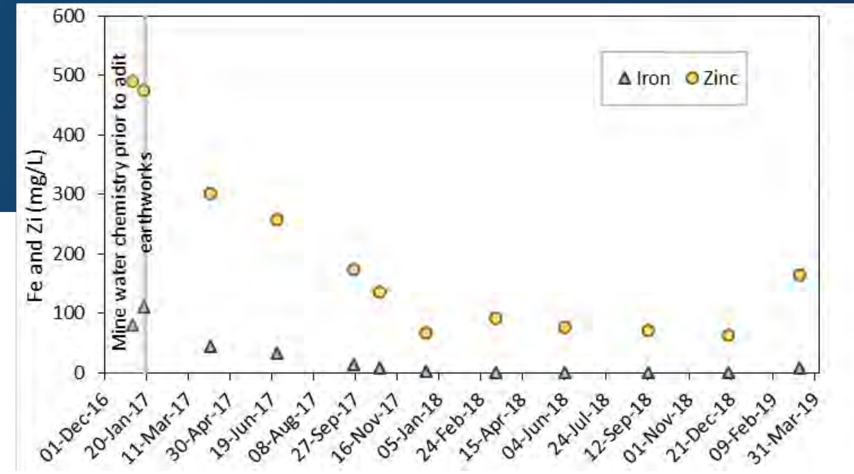
# Void Carbon Dioxide & Rainfall

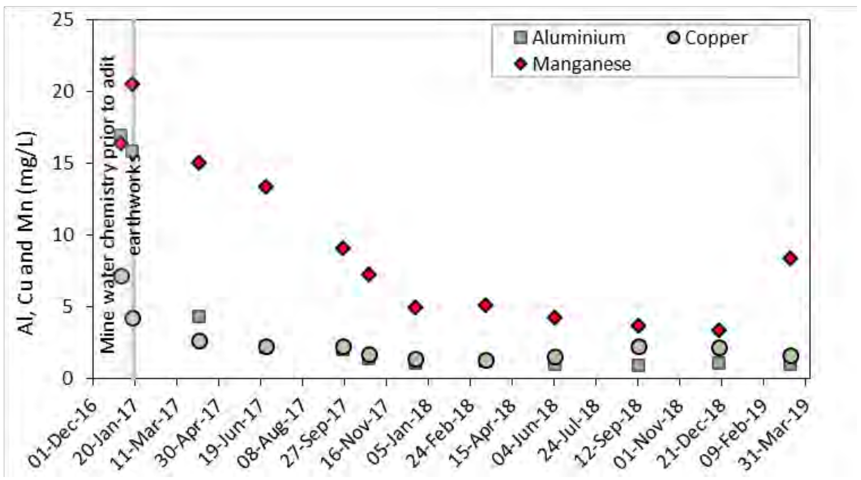


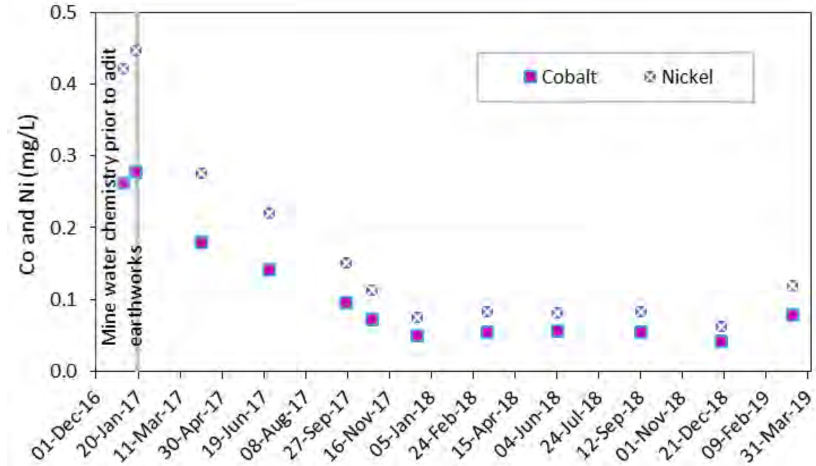
# Case Study: Nevada

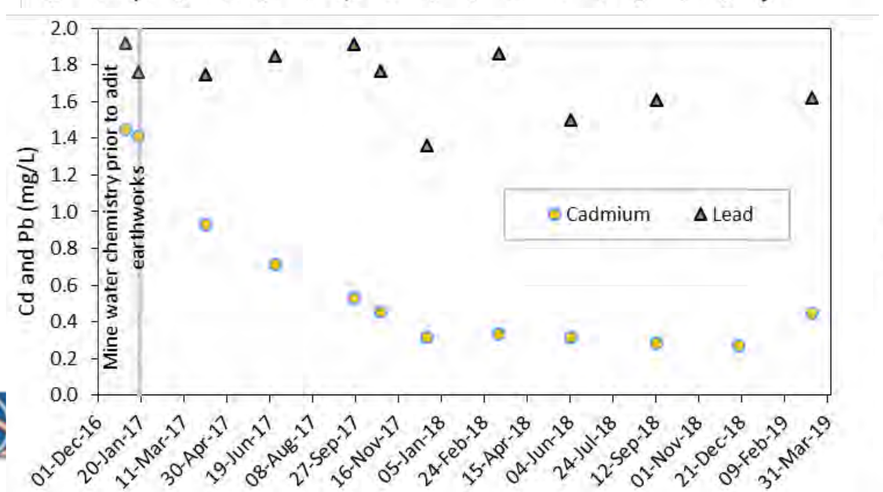


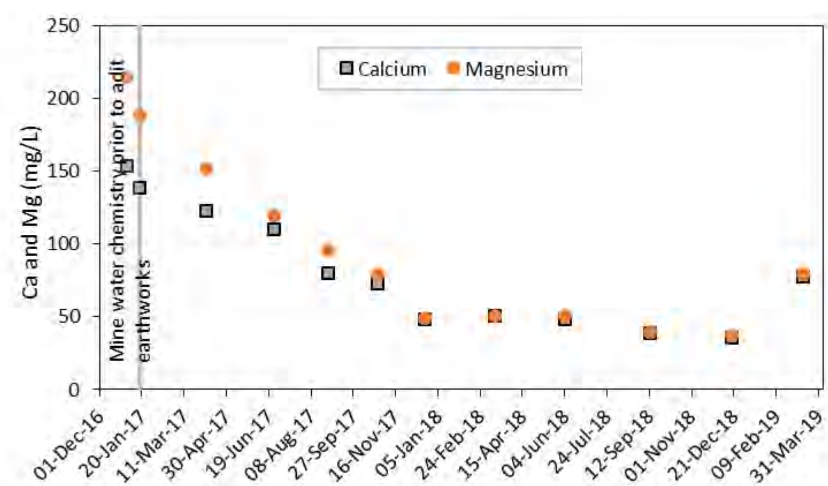

SO4 (mg/L)
Sulfate
Mine water chemistry prior to adit earthworks


Fe and Zi (mg/L)
Iron
Zinc
Mine water chemistry prior to adit earthworks


Al, Cu and Mn (mg/L)
Aluminium
Copper
Manganese
Mine water chemistry prior to adit earthworks


Co and Ni (mg/L)
Cobalt
Nickel
Mine water chemistry prior to adit earthworks


Cd and Pb (mg/L)
Cadmium
Lead
Mine water chemistry prior to adit earthworks


Ca and Mg (mg/L)
Calcium
Magnesium
Mine water chemistry prior to adit earthworks

# Water Chemistry Overview

- Weakly acidic water.
- High $CO_2$ in water (due to void gas) is rapidly released as water exits adit and pH rises from 4.5 to 4.8 within 30 minutes.
- Eh (redox potential) of water remains quite oxidised (started at ~600 mV and down to ~500 mV), despite low or no oxygen.
- No sulfide in water (only sulfate).
- Structural timbers are not significantly affecting water chemistry, only void gas composition.
- It is evident that this is not a reducing environment, but a low oxygen (suboxic) environment.
- Oxygen removal has been via an oxidising process not a reducing process (exactly as in a waste rock pile).
- Decrease in Eh (redox potential) of water probably partially related to loss of dissolved oxygen in low oxygen atmosphere (also increase in pH).

# Degree of Difficulty

- 1.0 Million tonnes of PAF waste rock end-dumped onto side of hill.

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- 7-8 air entry sites.

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- Inert atmosphere approach = Witchcraft.

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- 7-8 air entry sites.
- Inert atmosphere approach = Witchcraft.

- Inert atmosphere technology is a simplified waste rock encapsulation strategy, with a greater degree of success than most waste rock piles, at most underground mine sites.
- Risk to human health of a sealed underground mine = risk of standing on an well constructed waste rock pile with low internal oxygen concentrations.
- Equivalent risk to a low oxygen “confined space”.

# Conclusions

- Inert Atmosphere Systems offer a low complexity, low risk and cost effective alternative approach to hydraulic seals and water treatment in perpetuity for underground mines.
- Pollution reduction strategy is equivalent to improved waste rock construction techniques, but likely with a far lower degree of difficulty and cost.
- Stage 1 works could be completely passive at some sites, if air entry and drainage controls alone are sufficient to lower ARD generation to acceptable levels.
- Stage 1 works could be implemented in conjunction with passive treatment systems.
- Stage 2 implementation will be important for stopping ARD at treatment in perpetuity sites.
- The technique can be applied to the closure of recent or historic underground mines and probably quite safely to the unused portions of active mines.
- Mining can easily resume as the approach is rapidly reversible.
- Simultaneously lower water discharge and improve water quality from mine workings.
- Simultaneously lower public safety risks with mine sealing works.
- Low impact on site heritage values.

# Contact Details

Jeff Taylor - Director

jeff.taylor@earthsystems.com.au

Phone: +61-402 158 682

www.acidmetalliferousdrainage.com

www.earthsystemswater.com

www.earthsystems.com.au

www.esanalytical.com

# Evolving kinetic testing methods to address risk for site-specific, sustainable closure planning

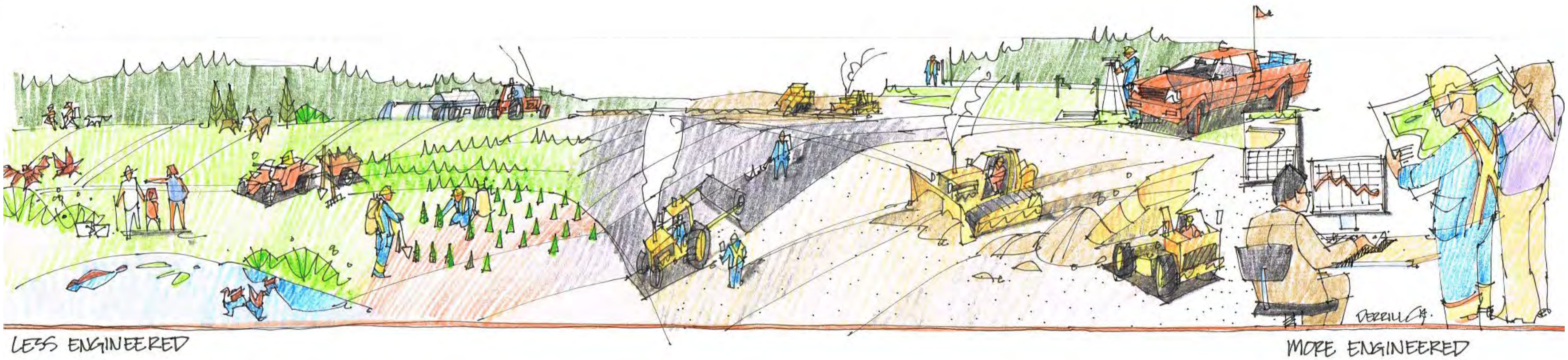
Jared Robertson, Kirstine Malloch,
Ursula Salmon, Mike O'Kane

May 2, 2019

Acid and Metalliferous Drainage
Management Mini Symposium

okane

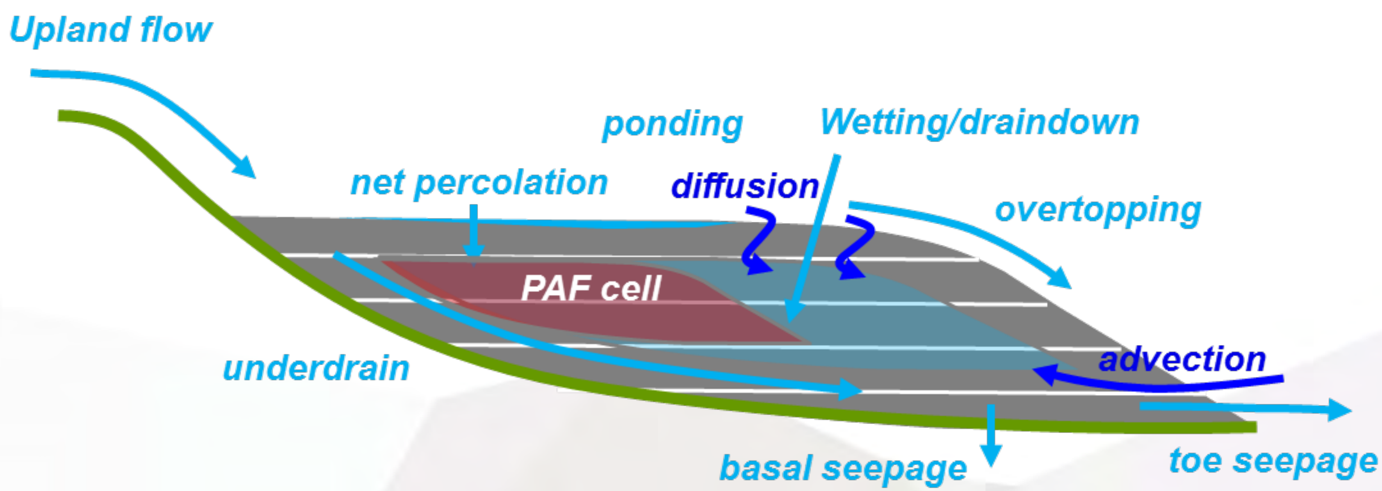
# Three Key Discussion Themes




1. Some Background for Context
2. Kinetic Testing and Quantifying Risk
   - Current Challenges
3. New Method
   - Advanced Customizable Leach Columns (ACLCs)

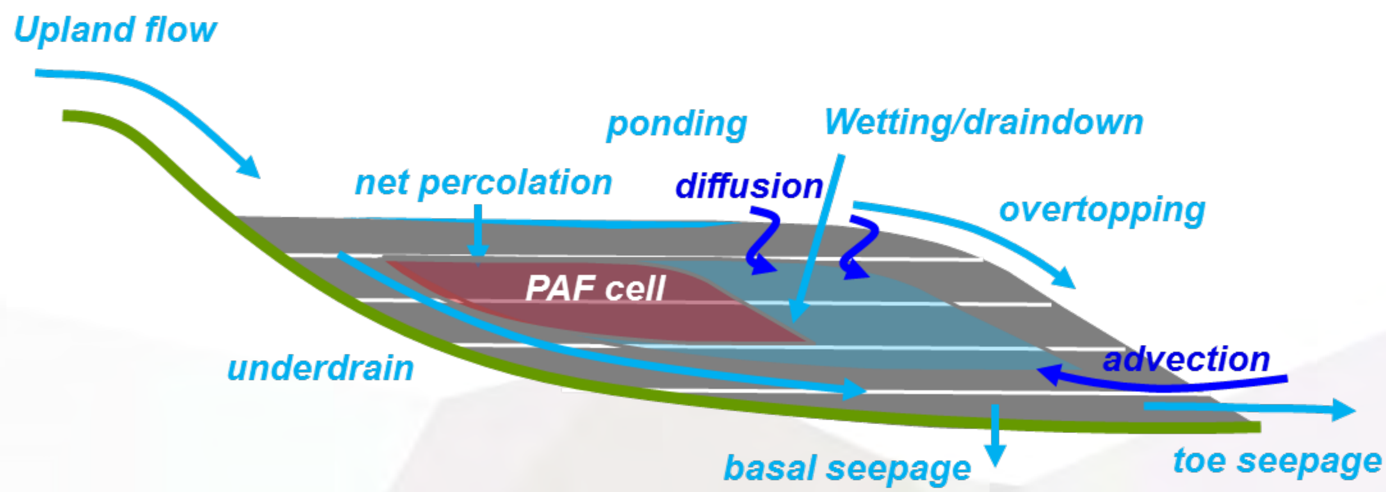
# Background for Context

- Acid rock drainage (ARD) assessments often focus on geochemistry
- However, oxidation of waste rock needs $O_2 + H_2O$
  - $O_2$ availability is a function of PSD, water content, climate, geometry, internal structure, etc.

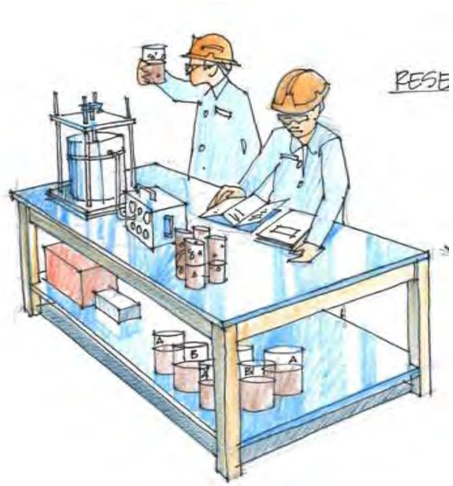


# Background for Context

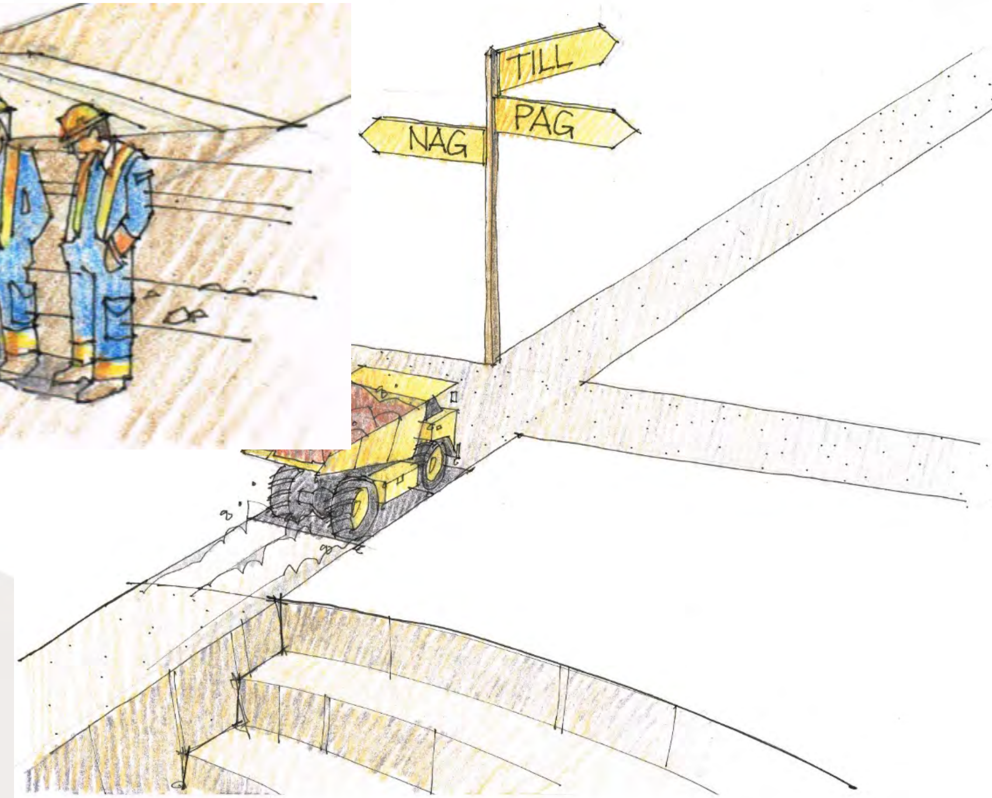
- Acid rock drainage (ARD) assessments often ignore:
  - The physical story (e.g., rock physical properties, internal structure)
  - The site-specific relationship between geochemistry, atmosphere, and water balance



# Background for Context



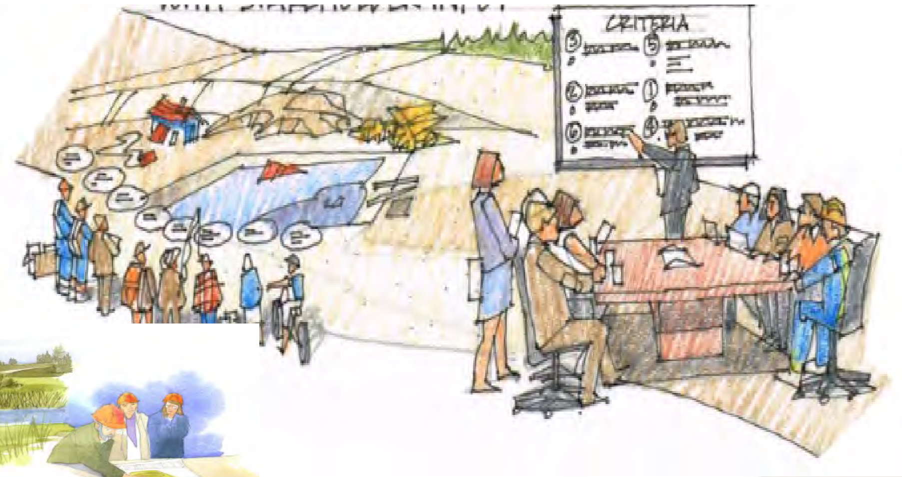
## Laboratory Conditions




## Field Conditions

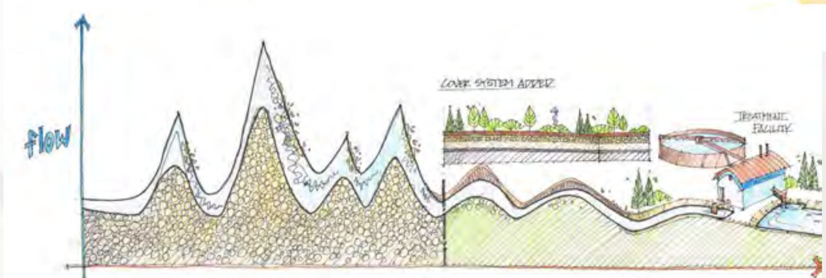
# Background for Context

- **The Desire**
  - Utilize laboratory testing to better inform on seepage water quality for field-scale conditions




***Design Criteria***

***Land Use***




***Effluent Treatment***

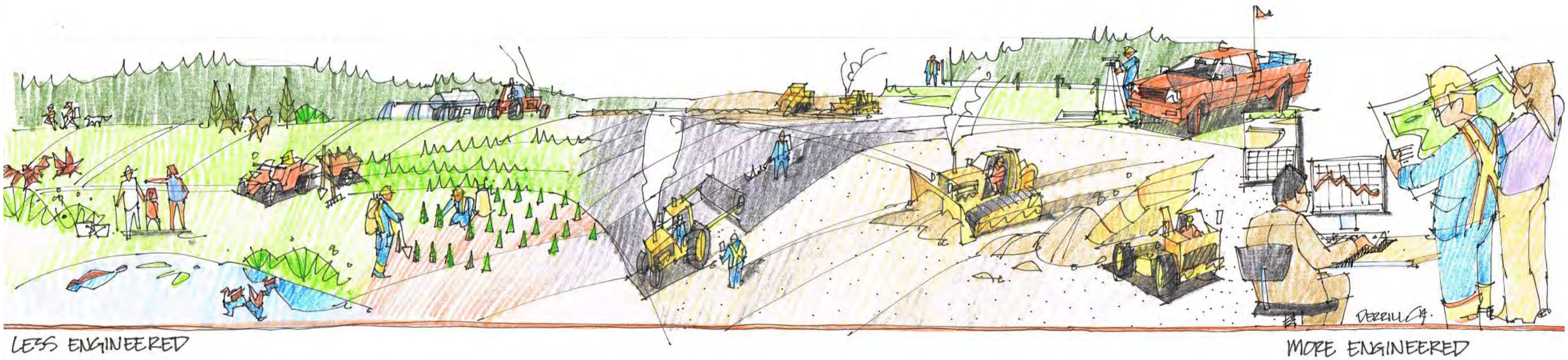


okane

# Background for Context

- **The Ideal**
  - Establish a rigorous foundation for designing smaller-scale metal-leaching testing for scaling up to the field
- Has our widely used metal leaching testing (e.g., humidity cell testing) been successfully scaled up to the field?
- The **physical setting** of our waste material strongly influences seepage **water quality**

# Three Key Discussion Themes

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2. ***Kinetic Testing and Quantifying Risk***
   - ***Current Challenges***
3. ***New Method***
   - ***Advanced Customizable Leach Columns (ACLCs)***

# Kinetic Testing: Limitations

- Current Methods:
  - Humidity Cells (ASTM D5744-96)
  - Columns (e.g., AMIRA, 2002)

# Kinetic Testing: Limitations

- Current Methods:
  - Humidity Cells (ASTM D5744-96)
  - Columns (e.g., AMIRA, 2002)
- Limitations include:
  - Oxidation rate based on sulfate release
    - Common $SO_4$ precipitates may lead to under/over estimation of rate
  - Samples are crushed
    - Alters the material’s hydraulic properties (WRC, $k_{sat}$)
    - Exposes more reactive mineral surface than in the field
  - Liquid:solid ratios generally much higher in the laboratory than in the field


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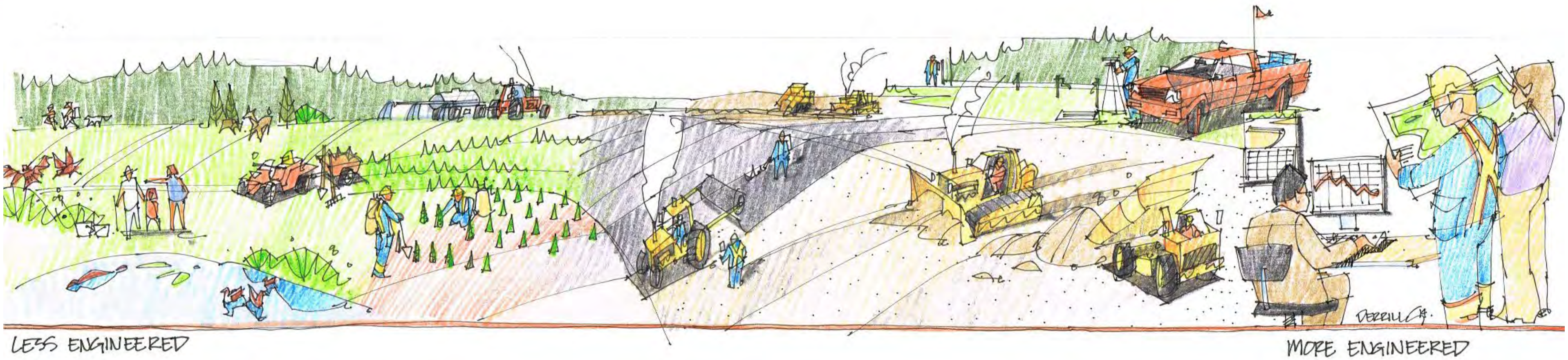
# Kinetic Testing: Limitations

- Current Methods:
  - Humidity Cells (ASTM D5744-96)
  - Columns (e.g., AMIRA, 2002)
- Multiple scaling factors required
  - Temperature
  - Humidity
  - Gas Composition
  - Hydrology
  - Climate
- Adds uncertainty to the assessment

# Three Key Discussion Themes

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# Advanced Customizable Leach Columns

## Saskatoon ACLC Lab




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# Advanced Customizable Leach Columns

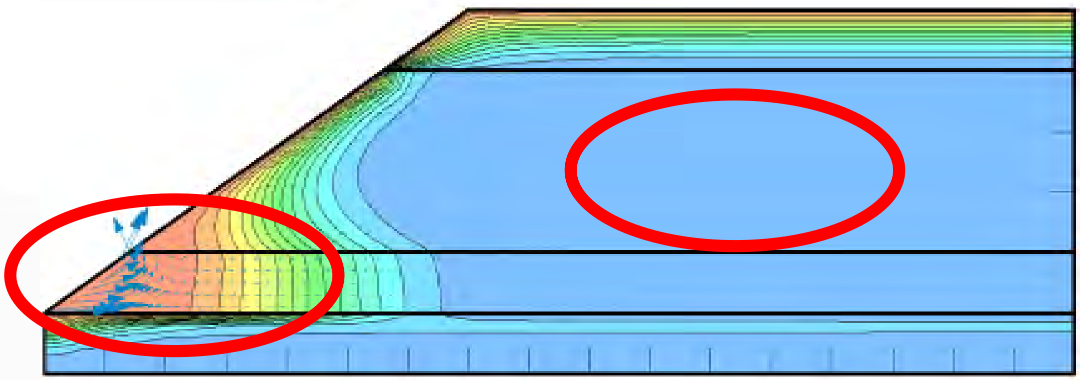
**Perth ACLC Lab**

# ACLC Capabilities

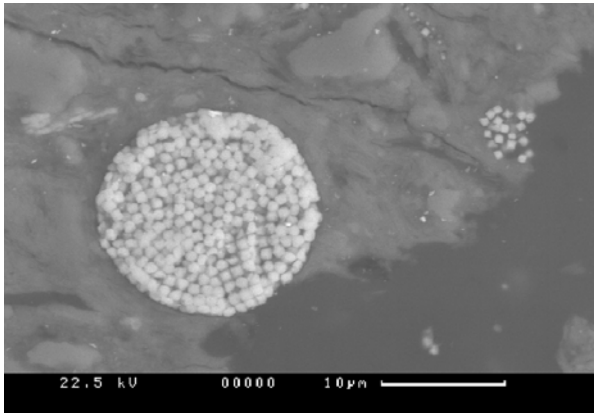
- Customizable Parameters
  - Gas flowrate and composition
  - Enclosure temperature
  - Matric suction / porewater pressure
  - Water addition regime (and L:S ratio)
  - Humidity
- Monitoring Capabilities
  - Inlet and outlet gas concentration and flow
  - Column matric suction / porewater pressure
  - Column temperature
  - Composition of leachate
- Material Characterization
  - Geochemical and physical properties
  - Oxidation rates from gas consumption

# Case Study #1

- Aim: To understand the effect WRP construction has on drainage chemistry
- Experiment: Replicate two locations of a WRP in the ACLCs
  1. The exterior which freely interacts with the environment (21% $O_2$ – freely oxidizing conditions)
  2. The interior where oxygen and gas flux are limited (~1% $O_2$ – anoxic conditions)
- Compare results to AMIRA columns



# Case Study #1




- Friable mudstone (high surface area)
- Smaller particle size in the field limits oxygen ingress
- Framboidal pyrite (higher surface area – more reactive)

*ABA Characteristics*

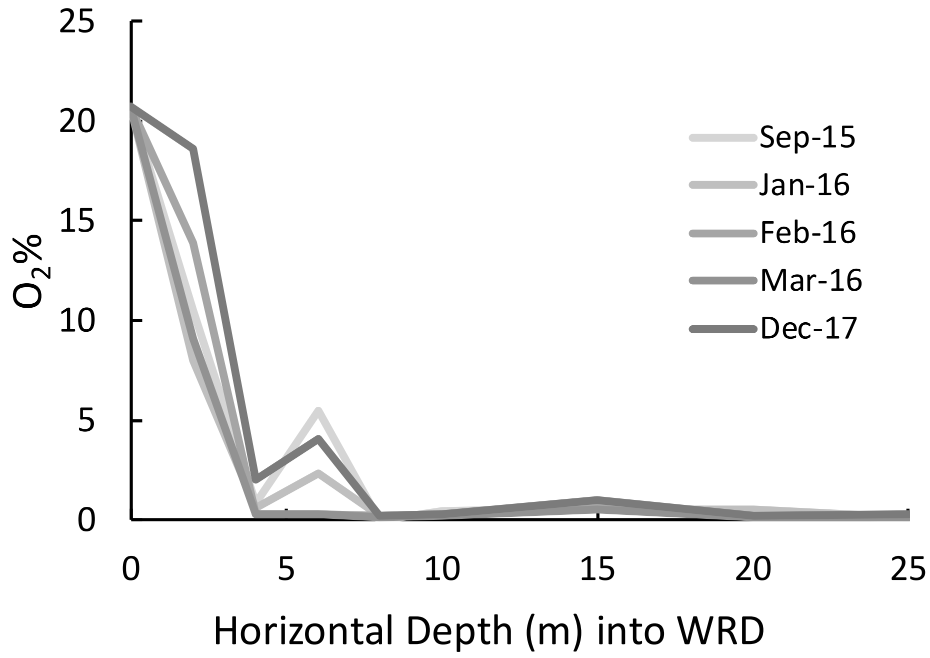
- Total S% 1.6
- NAG pH 2.5
- ANC -4
- NAPP 50 (PAF)



okane

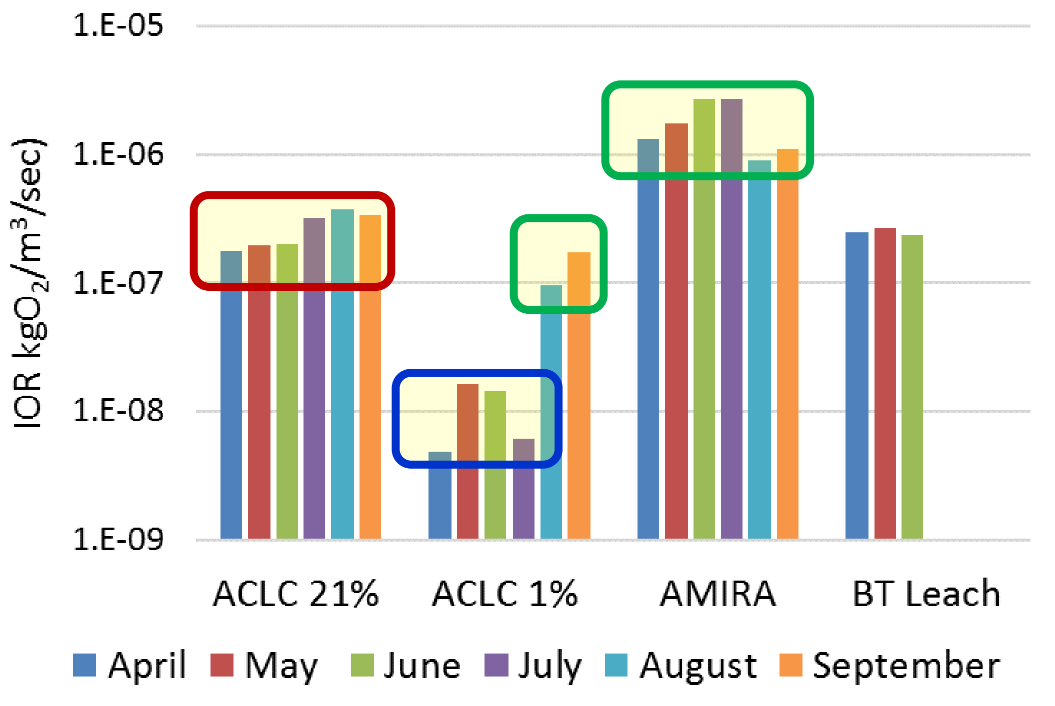
# Case Study #1

- ACLC experiment designed to meet field conditions
- Field Conditions
  - moisture content 12-14 wt%
  - Temp ~10 C
- Oxygen content measured in the field
  - $O_2$ ~21% at surface, <5% internal
- Model these two end member $O_2$ conditions in the ACLCs



# Case Study #1 – Oxidation Rates

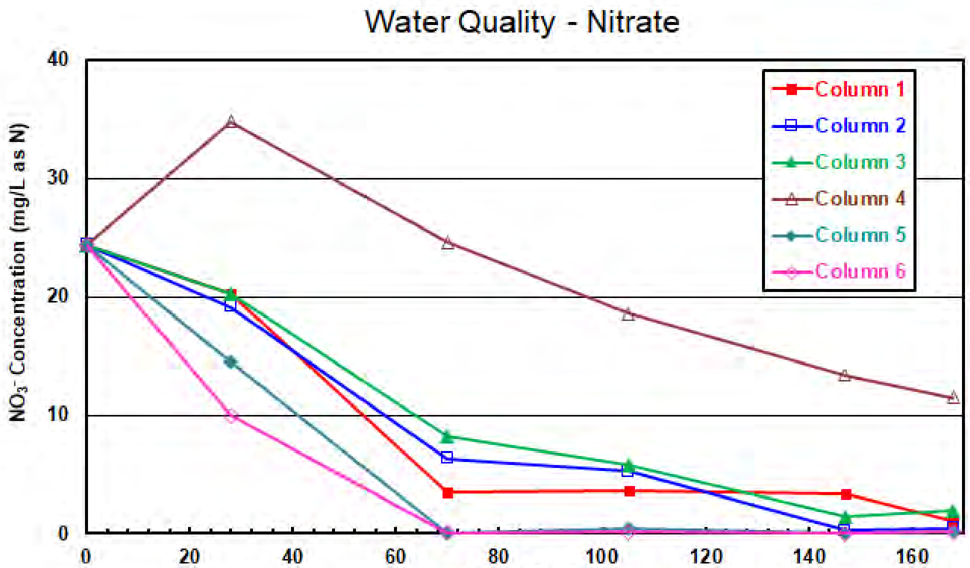
- Comparison of oxidation rates between ACLCs, AMIRA columns, and large columns
- IOR = Intrinsic oxidation rate

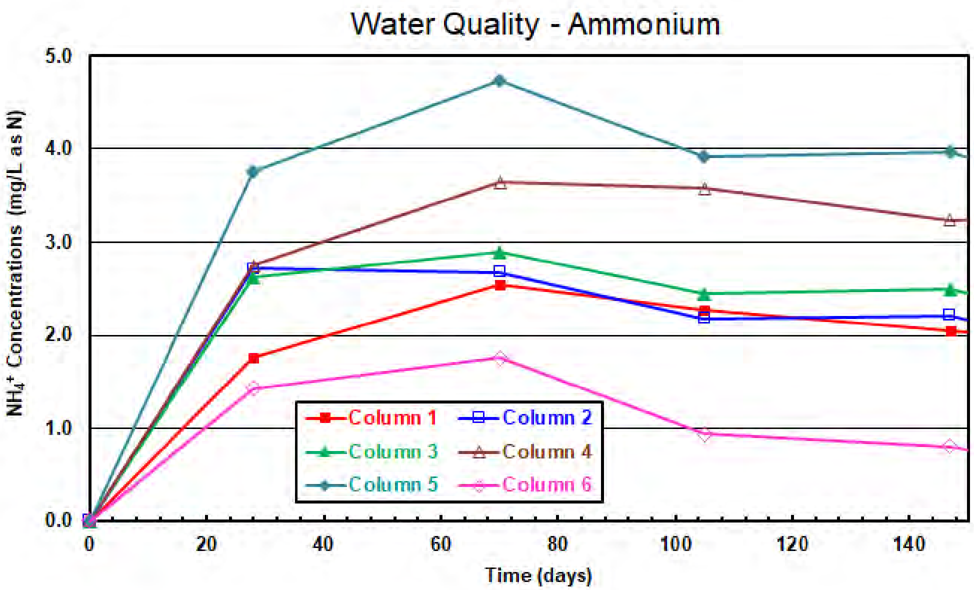


# Case Study #2

- Columns operated at suboxic (0.5 to 1.0% $O_2$) conditions
- Testing the feasibility of exploiting suboxic conditions for $NO_3$ and Se removal
  - Reduction of $NO_3^-$ to $NH_4^+$
  - Reduction of $SeO_4^{2-}$ to $Se_{(s)}$
- Develop design guidelines

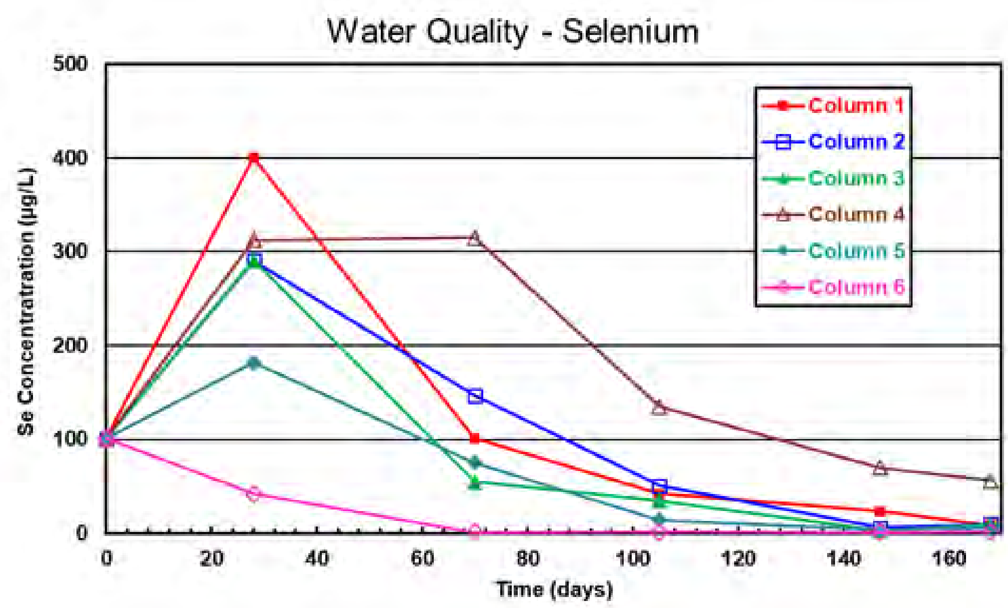
# Case Study #2 – Nitrate Reduction



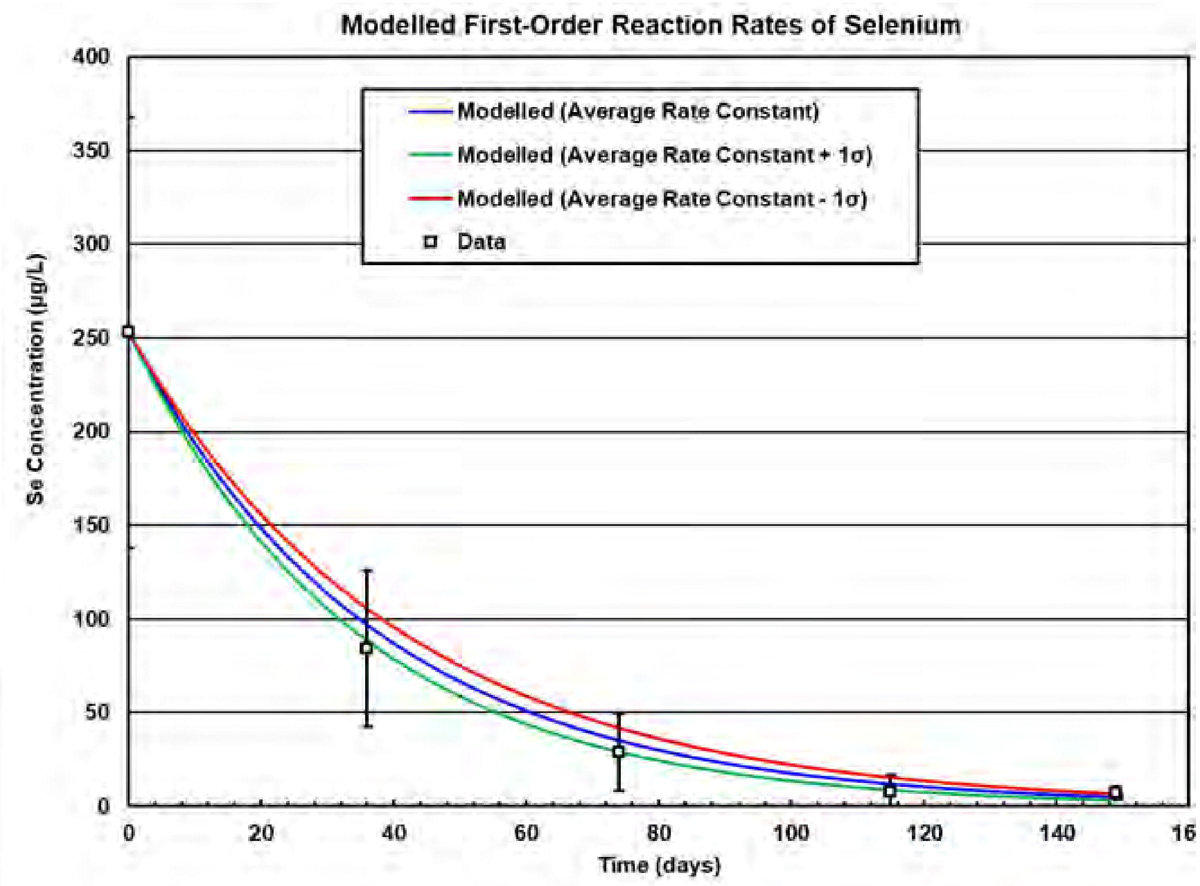

- Influent contains:
  - 25 mg/L $NO_3^-$
  - No NO2- or $NH_4^+$
- Nitrate reduction in column leachate is evident
- $NO_2^-$ and $NH_4^+$ generated in columns

# Case Study #2 – Selenium Reduction




- Column Se concentrations initially >> influent Se
- Initial flushing event likely flushed oxidation products
- Evident Se reduction after initial flush of oxidation products
- Se reduction likely precipitating elemental Se

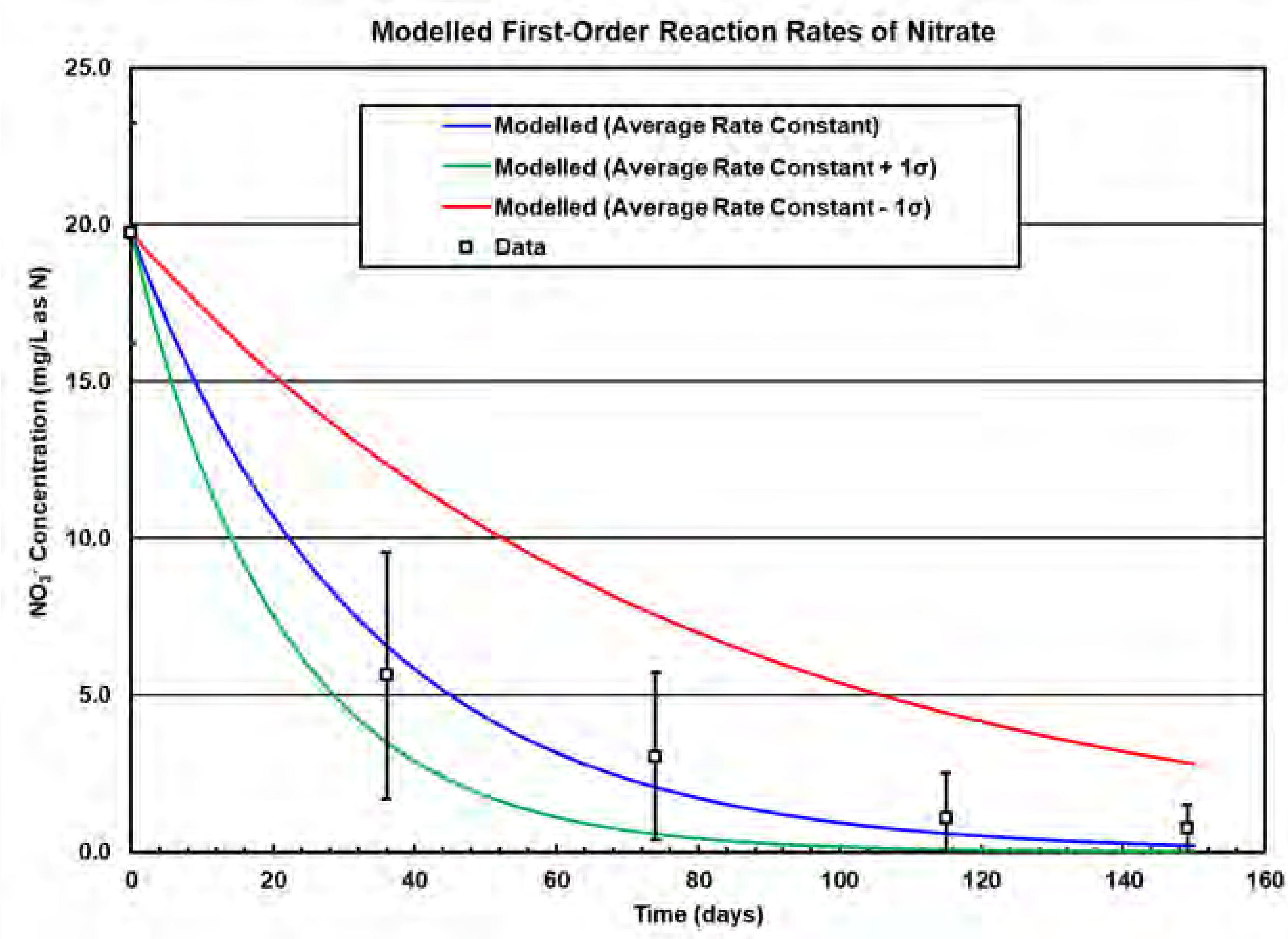
# Case Study #2 - Rates of Selenium Reduction




- Se reduction rates demonstrate the importance of hydraulic residence time
- Informs on what conditions are needed to achieve required Se reduction

First order reaction: $C = C_0e^{-kt}$ ; $k = 0.03\ day^{-1}$

# Case Study #2 - Rates of Nitrate Reduction



# Conclusions

- The physical setting of waste rock material strongly influences seepage quality
- Current industry standards do not control for the physical setting
- Applying these results adds uncertainty
- ACLCs aim to decrease the gap between laboratory and field conditions
- Fewer scaling factors, less uncertainty
- Still more work to be done!

# Thank You!

# MORRO DO OURO SITE ARD MANAGEMENT PROGRAM

**2018 ICARD – PRETORIA - SOUTH AFRICA**

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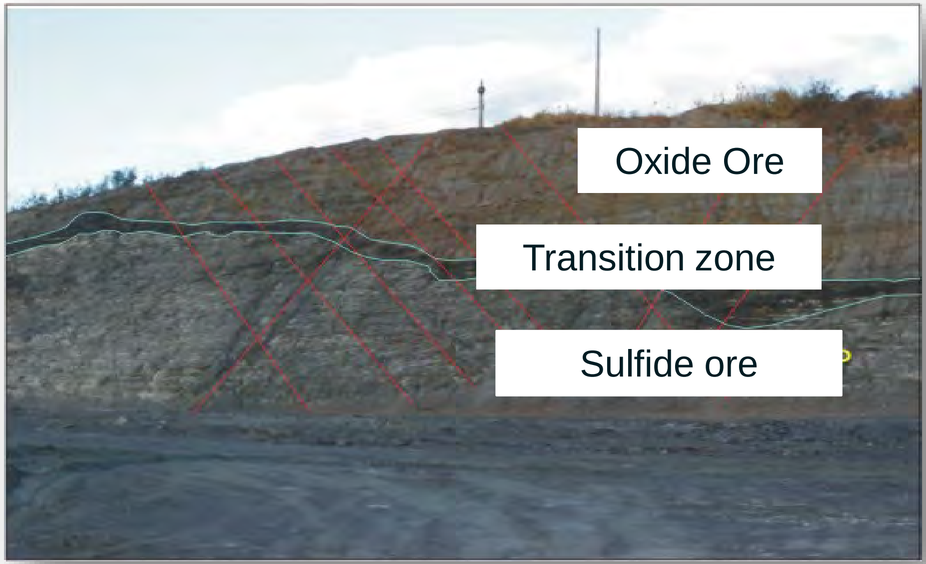
# Morro do Ouro Site Location

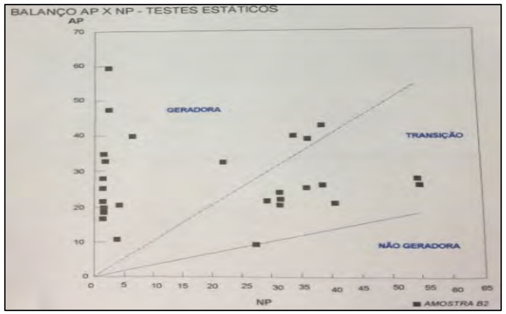

# Geology




# ARD Research Program

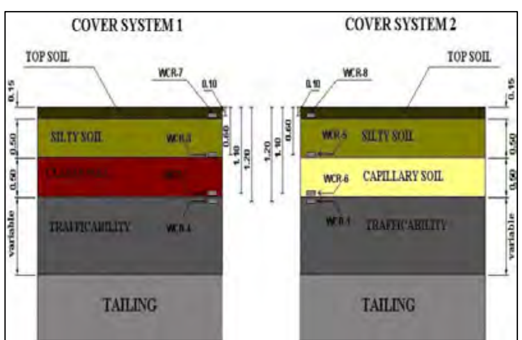
Testing Timeline

**1991-1993**

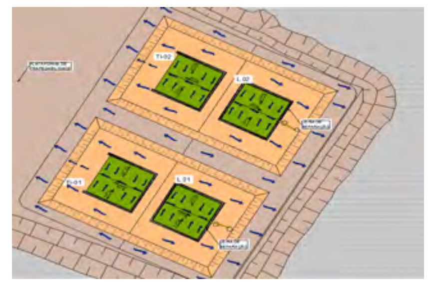


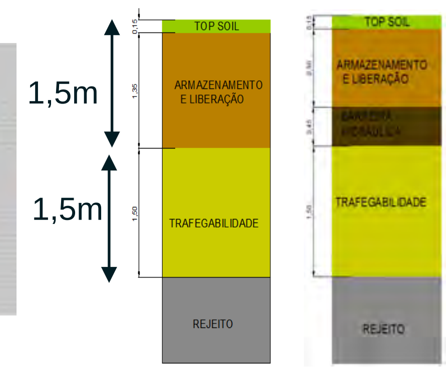

**1994 - 1997**

**2010 - 2018**




Field test installed at Santo Antonio dam facility to investigate potential covers:



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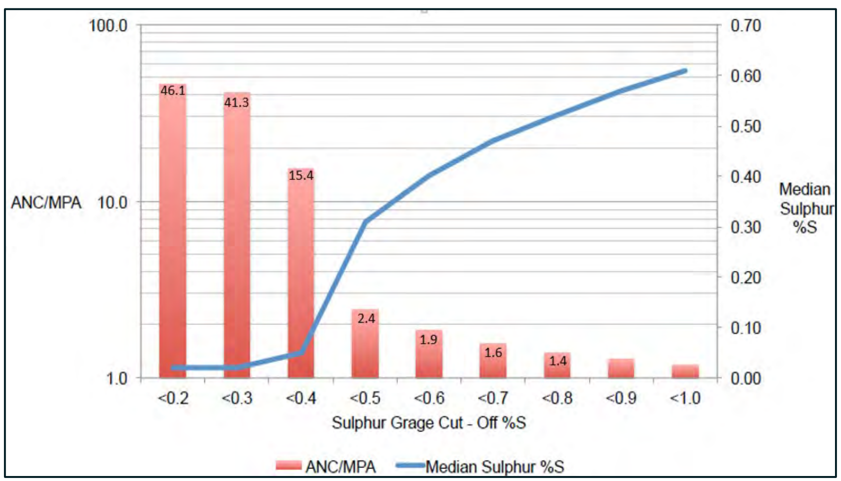
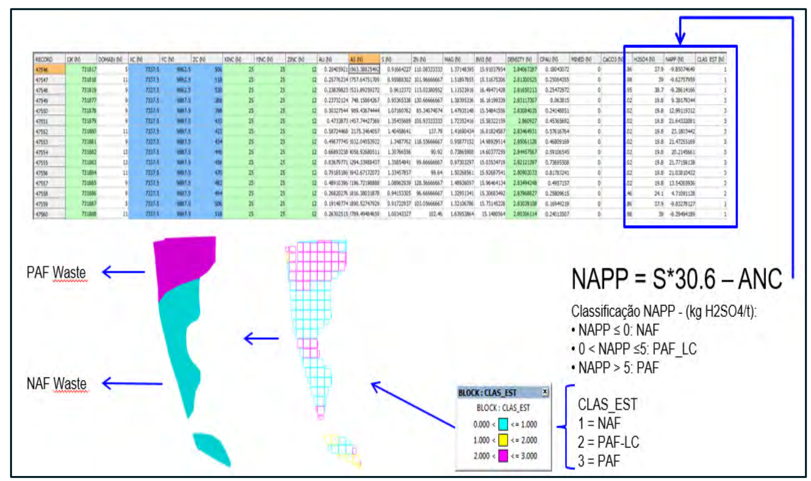
# Integration of the Research Program Results in the Mine Processing Design

# Development of S and ANC Database for Mining Plan

1. Sulfur and acid neutralizing capacity (ANC) were conducted using the geological samples

2. In the absence of ANC data, a risk-based approach to define a workable and realistic S grade cut-off for NAF and PAF



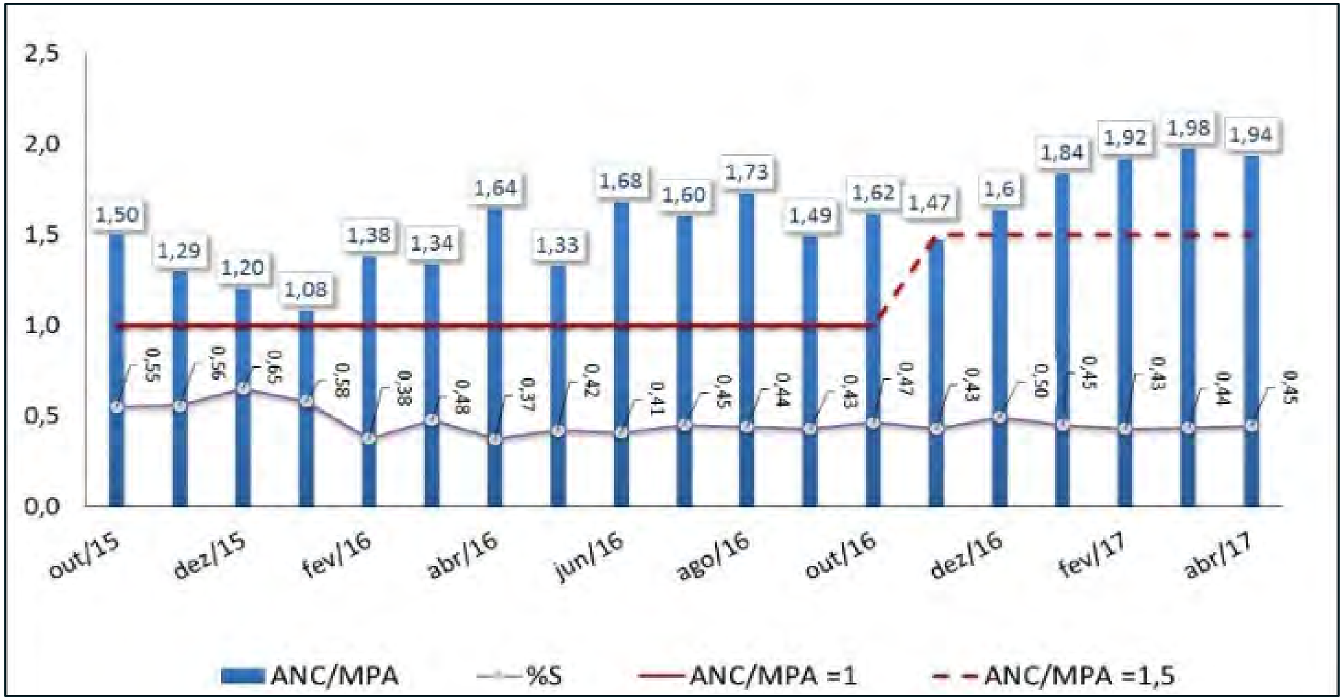



# Segregation of Sulfides

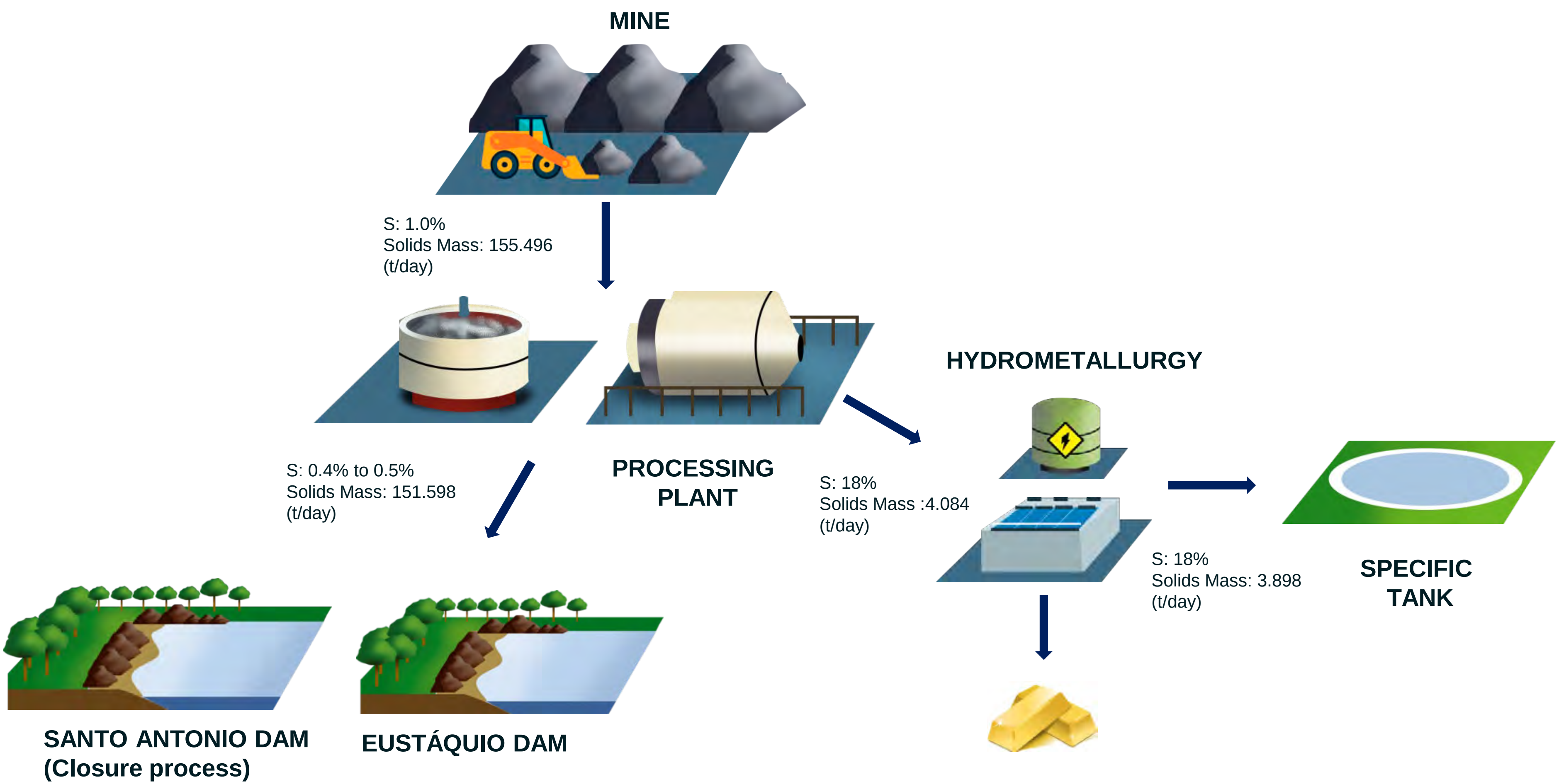
CIL tailings rich sulfide (18% S) are disposed in double sealed sumps (or specific tanks) excavated in bedrock and double lined with a local red clay and HDPE liner.

# Addition of Neutralizing Material to Ensure ANC/MPA > 1.0

Limestone is added in the processing plant to minimize the risk of acid generating in the dams. The acid base characteristics of tailings are routinely monitored.



# Processing Flowsheet

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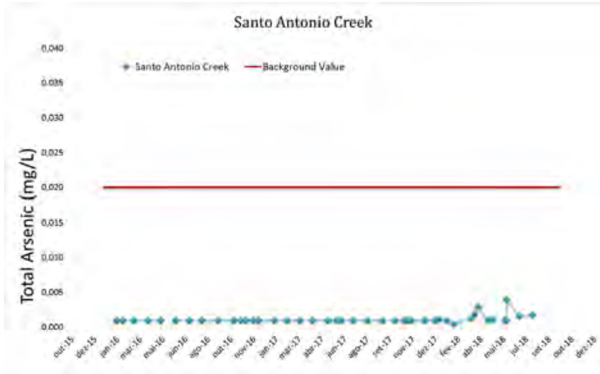
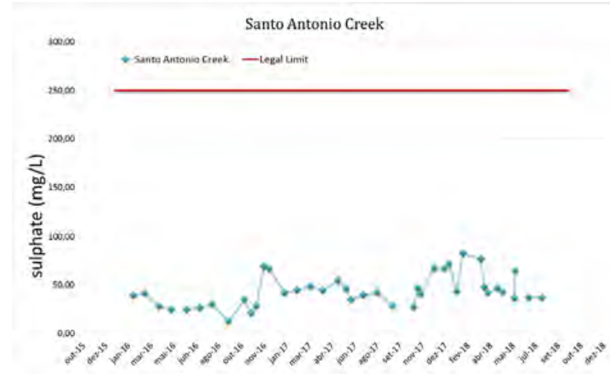
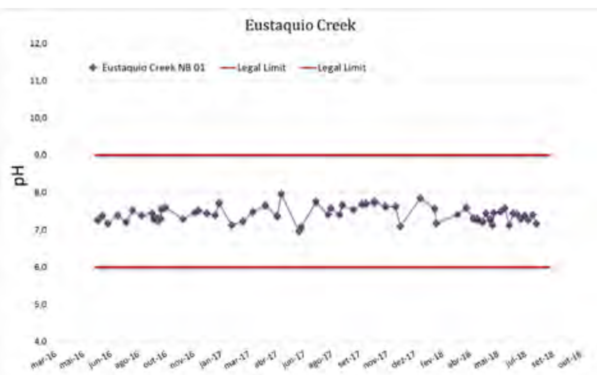
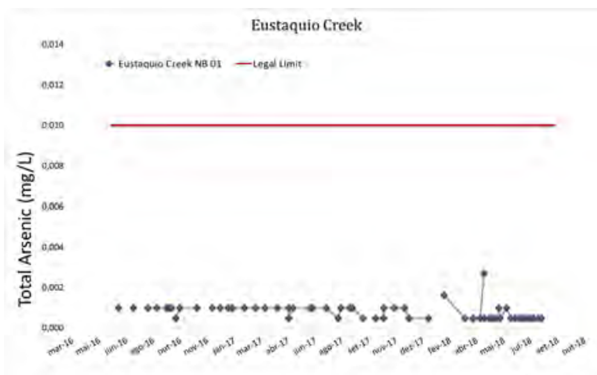
# Benefits Arising from the ARD Control Program

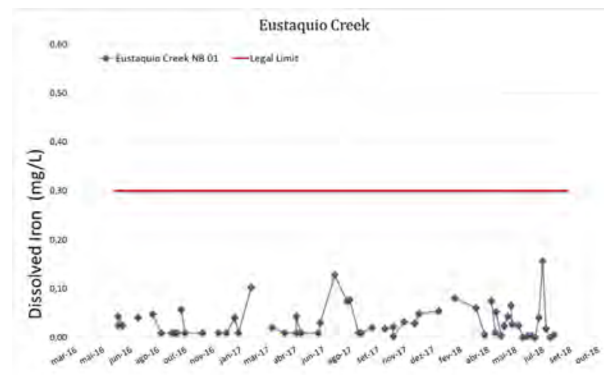
# Maintenance of Good Water Quality

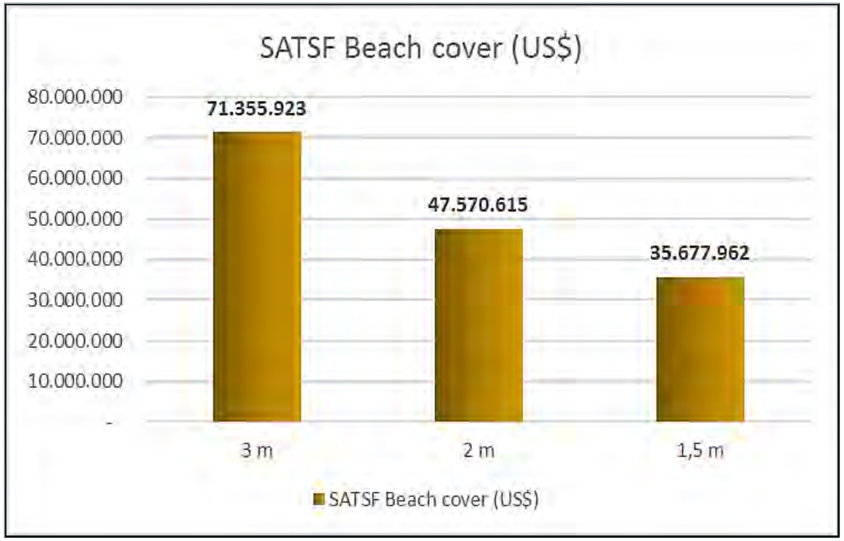



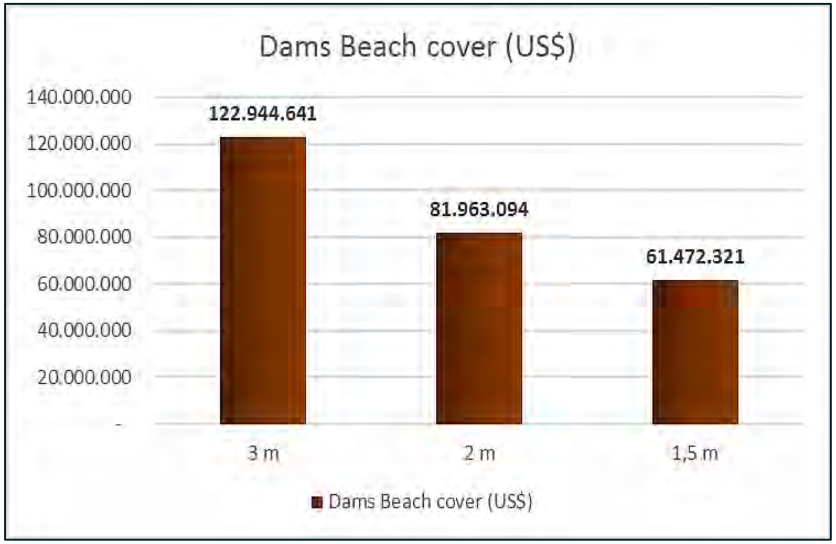



# Reduced Closure Costs



# Improved Perception Close to  Environmental Regulators

- Issuing of environmental permits early than planned,
- Environmental agency recommending other mining sites to visit Morro do Ouro site to learn about ARD controls;
- Last year, the overall site (extended) permit was renewed for the next 10 years

# Management Support

- ARD indicators like S and NAF/PAF ratios periodically monitored during production and mining department meetings;
- ARD control expenditures been integrated in the site business planning and into the decision making process.

*Summary of Expenditures with ARD control by Morro do Ouro site (1,000,000 U$)*

| Item | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | Total |
|---|---|---|---|---|---|---|---|---|
| Specific Tanks construction | 3.59 | 11.99 | 5.83 | 10.4 | 6.36 | 6.78 | 7.10 | **52.05** |
| Carbonate addition | 4.45 | 1.88 | 2.73 | 1.26 | 0.00 | 0.00 | 0.77 | **11.09** |
| Reagent addition | 3.16 | 6.24 | 7.38 | 6.89 | 4.95 | 4.99 | 5.35 | **38.96** |
| Geochemical assays | 0.45 | 0.29 | 0.29 | 0.31 | 0.41 | 0.77 | 1.10 | **3.62** |
| Consultancy support | 0.11 | 0.16 | 0.10 | 0.17 | 0.4 | 0.62 | 0.26 | **1.82** |
| Instrumented trial cover plot | 0.00 | 0.00 | 0.00 | 0.16 | 0.04 | 2.67 | 0.11 | **2.98** |
| **Total** | **11.76** | **20.56** | **16.33** | **19.19** | **12.16** | **15.83** | **14.68** | **110.51** |

# Final Remarks

- Taking account of ARD potential impacts in the early stages of mine planning has been key to properly define the best environmental and processing routes to mine a sulfide ore at Morro do Ouro site ;

- Support from management teams to incorporate ARD controls into their planning and budgets has been key for the success of the program;

- Benefits arising from a ARD Research program by far offset the investments made by the site, while maintaining its permit to operate and increasing its reputation close to the regulators

KINROSS 25 ANOS

SMI CMLR
Centre for Mined Land Rehabilitation

# Phytomining for nickel and other metals

Antony van der Ent

The University of Queensland
Australia

# What are hyperaccumulators plants?

- Hyperaccumulators are unusual plants that have extremely high concentrations of metals in their living biomass.

- Hyperaccumulator plants are known for elements such as arsenic, cobalt, copper, manganese, nickel, selenium, thallium and zinc.

- Hyperaccumulators have been discovered all around the world on mineralized soils and outcrops.



# Nickel hyperaccumulator plants

- The greatest number of hyperaccumulators are known for nickel.
- This partly reflects the fact that worldwide surface exposures of naturally nickel-enriched ultramafic soils cover >3% of the Earth's surface.
- By 2015, approximately 400 such nickel hyperaccumulator plant species had been documented including: 130 species in Cuba, 65 species in New Caledonia and 59 species in Turkey.



# Nickel hyperaccumulator plants

- Some hyperaccumulators can reach up to 4% nickel in their leaves and up to 25% nickel in the sap.

- These are amongst the highest heavy metal concentration in any living tissue and it colors the sap and inner bark literally green from nickel ions.

- A mature tree can contain approximately 5 kilograms of pure nickel metal.

- The hyperaccumulator phenomenon is the more astonishing given the toxicity of this metal when soluble.



# Discovery of hyperaccumulators

- Testing for nickel hyperaccumulation is simple and cheap by using dimethylglyoxime (DMG) test paper, followed by quantitative analysis using ICP-AES or XRF.

- In practice DMG starts to show a pink colour from about 500 – 700 ppm nickel onwards. Strong reaction from 0.5% nickel onwards.

- Fairly rapid to test thousands of plant specimens (>500 per day is do-able with 2-3 people).



**DMG test paper turning purple when reacting with the sap of a hyperaccumulator plant.**

**Using handheld XRF to measure concentrations of nickel in a hyperaccumulator tree in the field in Indonesia.**


NICKEL
LOW GRADE SOIL

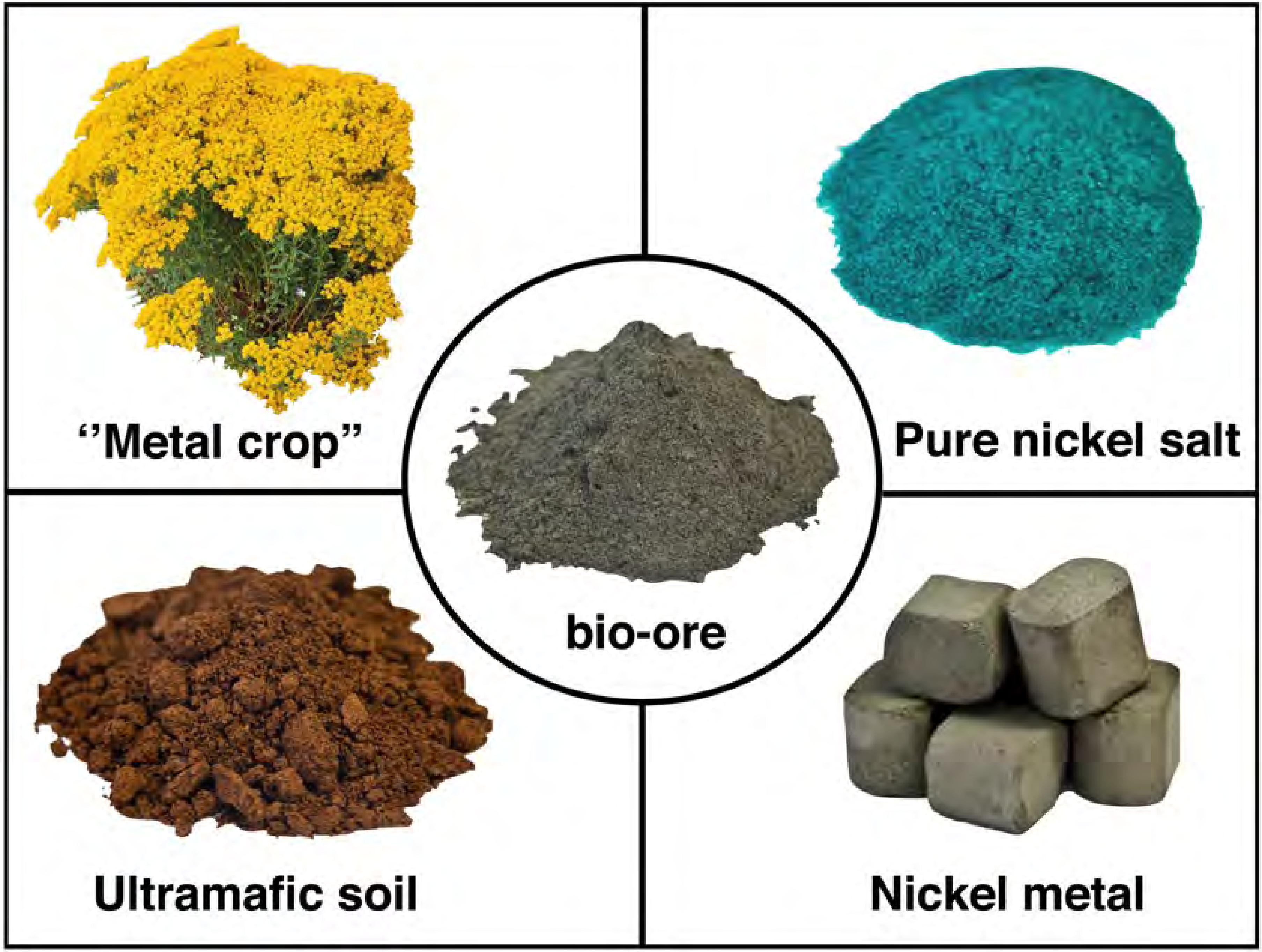
# Phytomining

- Phytomining (also called “metal farming”) employs hyperaccumulator plants to take up nickel into harvestable plant biomass.

- Harvesting, drying and incineration of that biomass then generates a high-grade bio-ore.

- As such hyperaccumulators are grown over (spatially large) sub-economic ore bodies or nickel-rich ultramafic soils.





''Metal crop''
Pure nickel salt
bio-ore
Ultramafic soil
Nickel metal

# Phytomining

- Economic feasibility of phytomining depends on the element market price, the annual yield per unit area (biomass produced and contained amount of target element) and the availability of surface areas enriched in this element.

- Based on field trials with nickel hyperaccumulator species such as Alyssum murale, we can harvest 4–5 t of dry matter per ha containing 2% Ni, yielding 80–100 kg Ni $ha^{-1}$.



# Phytomining on degraded or mined land

- Phytomining can form a first stage in the development of tropical lateritic mining projects, and then progress as part of the rehabilitation strategy during mine operation.

- This presents an opportunity for generation of cash flow from laterite projects during the project development phase.

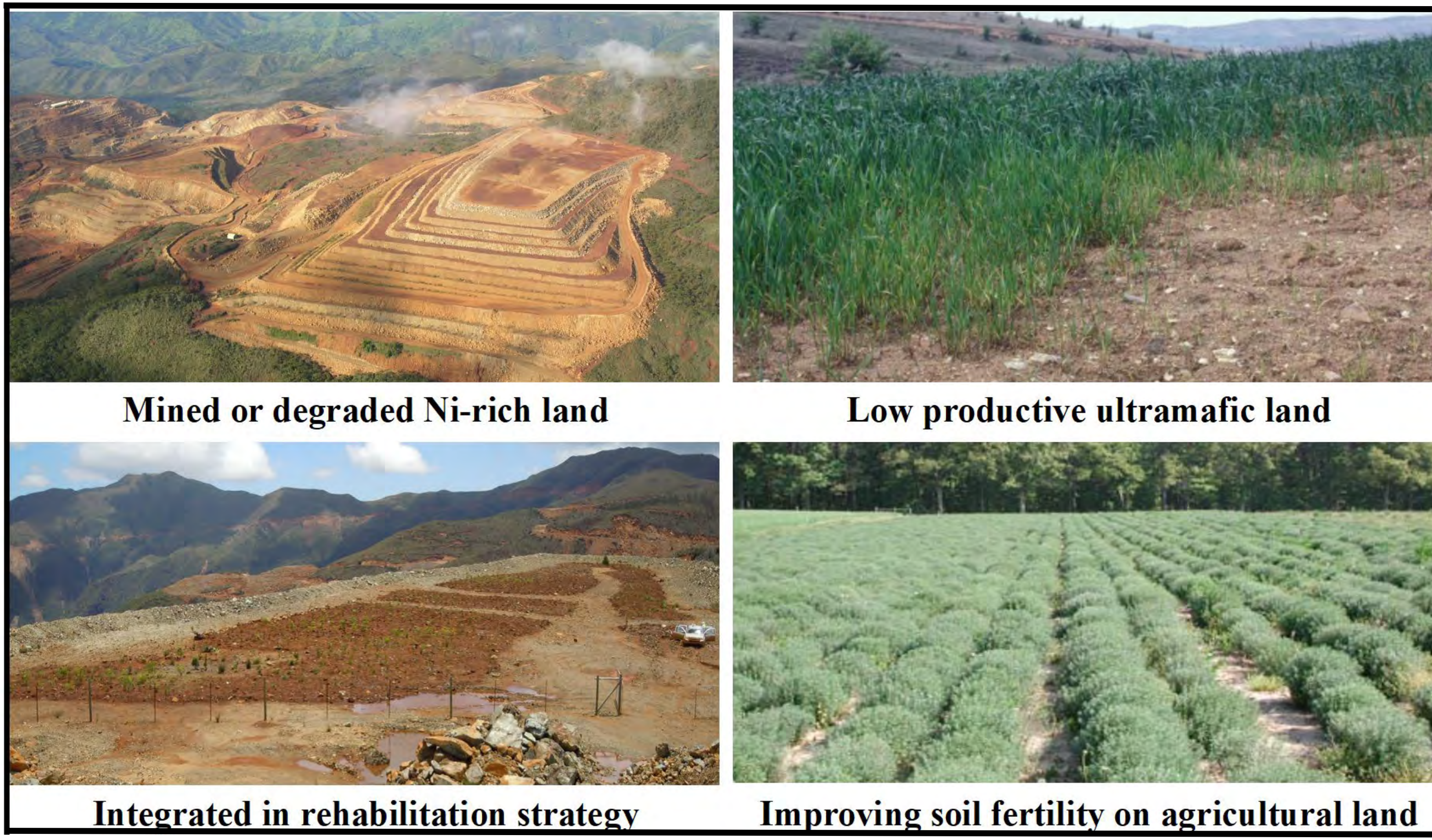
- It does not interfere with the mainstream project, as phytomining would initially use the overburden that would be cleared before extracting the underlying minerals.



# Phytomining on low-productivity agricultural soils

- Phytomining can also take place on large and relatively flat ultramafic areas, which have low productivity for food production.
- Phytomining here would be superior to conventional agricultural production, generating better economic returns to farmers.
- It should be emphasized that due to inherent infertility ultramafic soils have low economic returns if used for producing food crops such as wheat or rice.




Mined or degraded Ni-rich land
Low productive ultramafic land
Integrated in rehabilitation strategy
Improving soil fertility on agricultural land

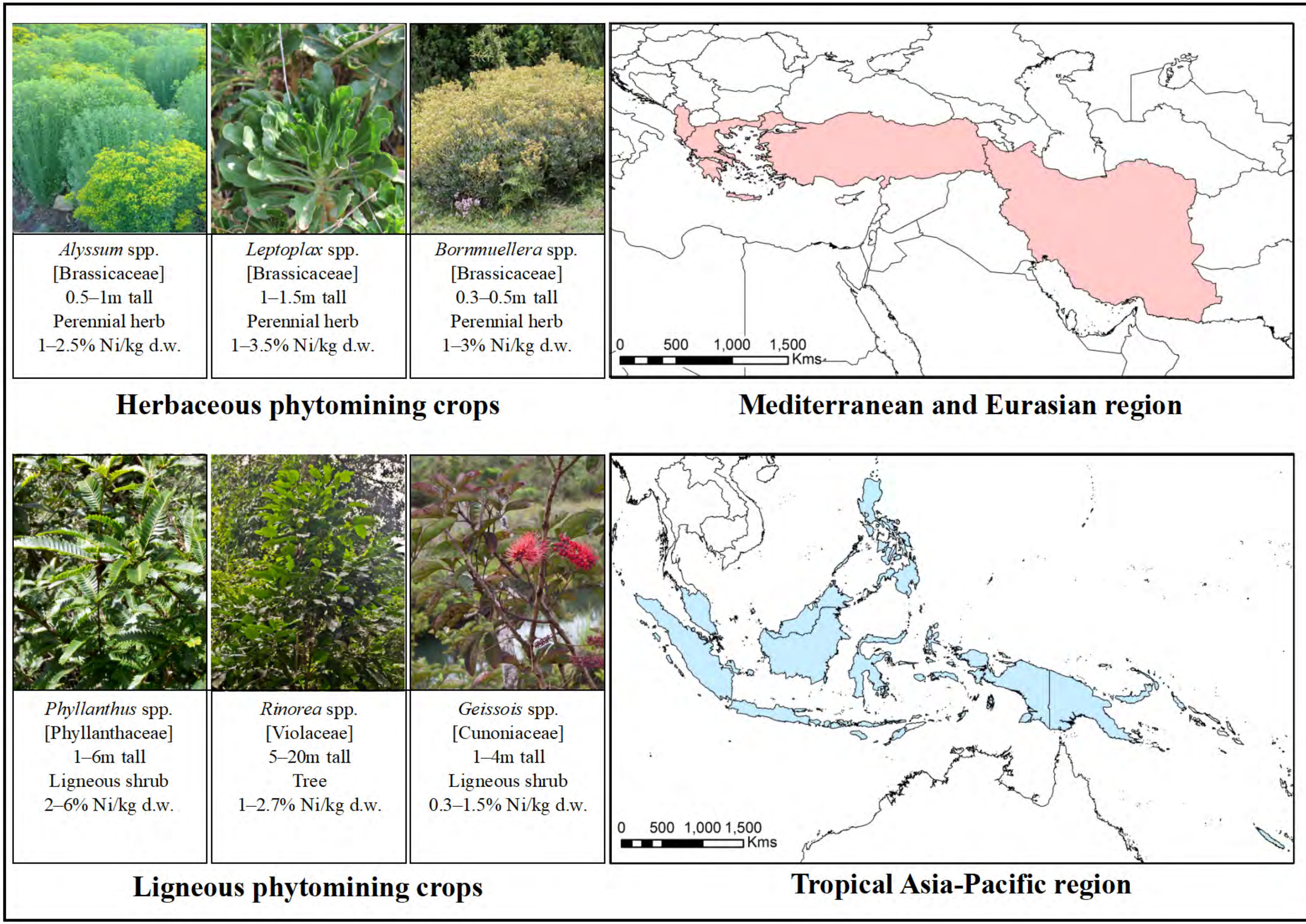

Alyssum spp.
[Brassicaceae]
0.5–1m tall
Perennial herb
1–2.5% Ni/kg d.w.
Leptoplax spp.
[Brassicaceae]
1–1.5m tall
Perennial herb
1–3.5% Ni/kg d.w.
Bornmuellera spp.
[Brassicaceae]
0.3–0.5m tall
Perennial herb
1–3% Ni/kg d.w.
0 500 1,000 1,500
Kms
Herbaceous phytomining crops
Mediterranean and Eurasian region
Phyllanthus spp.
[Phyllanthaceae]
1–6m tall
Ligneous shrub
2–6% Ni/kg d.w.
Rinorea spp.
[Violaceae]
5–20m tall
Tree
1–2.7% Ni/kg d.w.
Geissois spp.
[Cunoniaceae]
1–4m tall
Ligneous shrub
0.3–1.5% Ni/kg d.w.
0 500 1,000 1,500
Kms
Ligneous phytomining crops
Tropical Asia-Pacific region


Photo: A. Bani

IMAGE COURTEY OF: Dr. Rufus Chaney, USDA.


Photo: A. Bani

Photo: A. Bani


Rufus Chaney, USDA.

*Rufus Chaney, USDA.*

# Lateritic nickel mining in Southeast Asia

- There is a move from high-grade nickel-sulfide to low-grade nickel-laterite (ultramafic) ores, especially in the Asia-Pacific region.

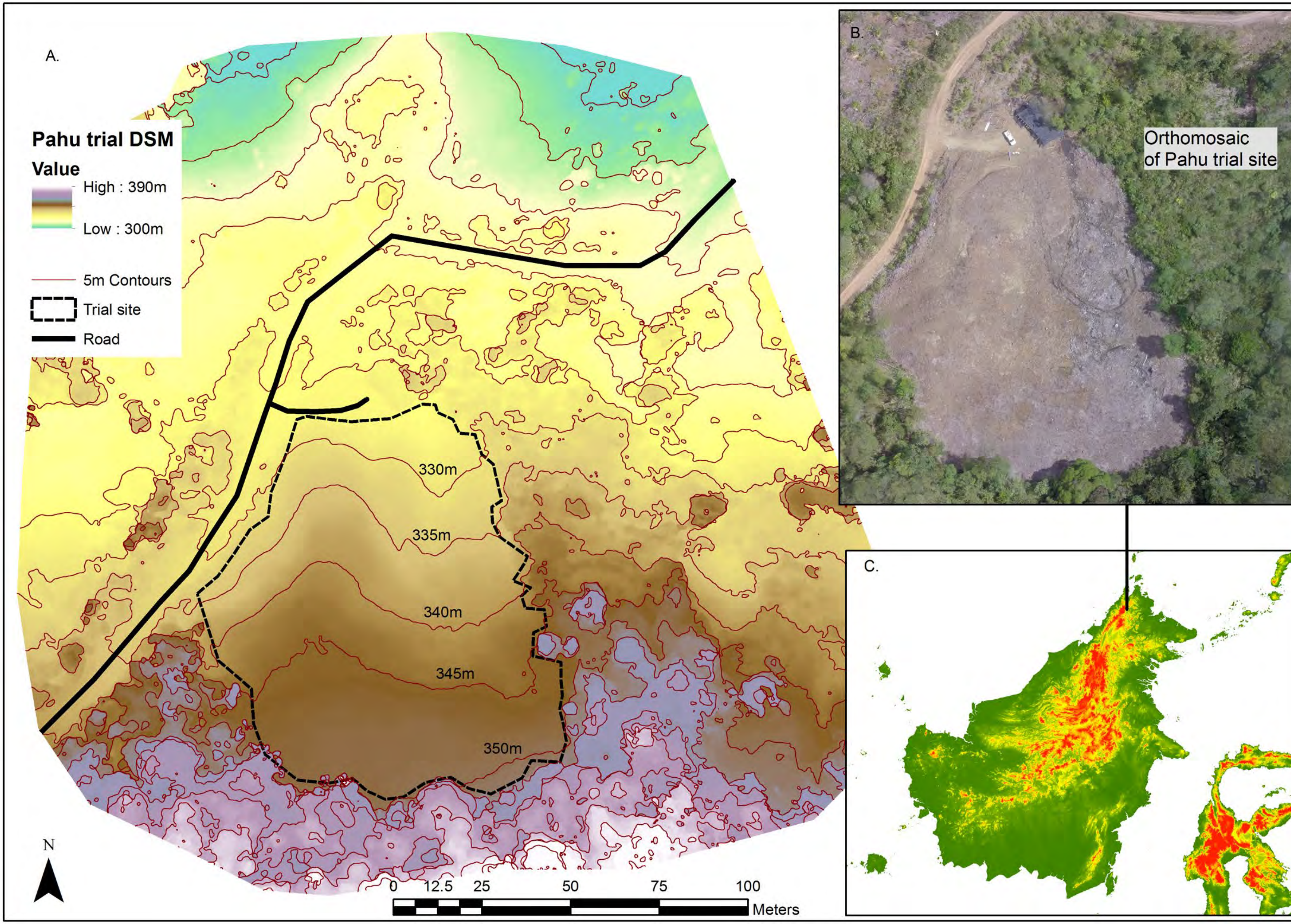
- Typical mining method is strip-mining of ultramafic soils.

- As such large areas are cleared and left bare after removal of ‘ore’ material.

- Rehabilitation comprises planting of a mix of native and introduced plant species – **<u>potential for introducing phytomining.</u>**




SELAMAT DATANG KE
GUNUNG TAMBUYUKON DAN
KEBUN HIPERAKUMULASI NIKEL
PUNCAK G. TAMBUYUKON
MT. TAMBUYUKON TRAIL
14 KM
14 KM



A.
Pahu trial DSM
Value
High : 390m
Low : 300m
5m Contours
Trial site
Road
330m
335m
340m
345m
350m
N
0
12.5
25
50
75
100
Meters
B.
Orthomosaic
of Pahu trial site
C.

**Nickel phytomining scientific trial near Pahu village.**

# Potential lifetime of an agromining operation

- The commercial returns from an agromining venture will be finite due to the diminishing concentrations of the target metal in the substrate.

- However, the time scale for economic agromining may be considerable:

  – For 1 ha with of 2000 mg $kg^{-1}$ total nickel over 1 meter depth, the resource contains about 30 t of nickel.

  – Crops with 5 t $ha^{-1}$ dry weight of plant material at 2% nickel yield 100 kg Ni $ha^{-1}$, which is only 1/300 of the total resource.



**Manual or machine harvesting of Ni-rich biomass from the mine site or "metal farm"**

**Processing of Ni bio-ore to produce high-value Ni compounds or pure Ni metal**

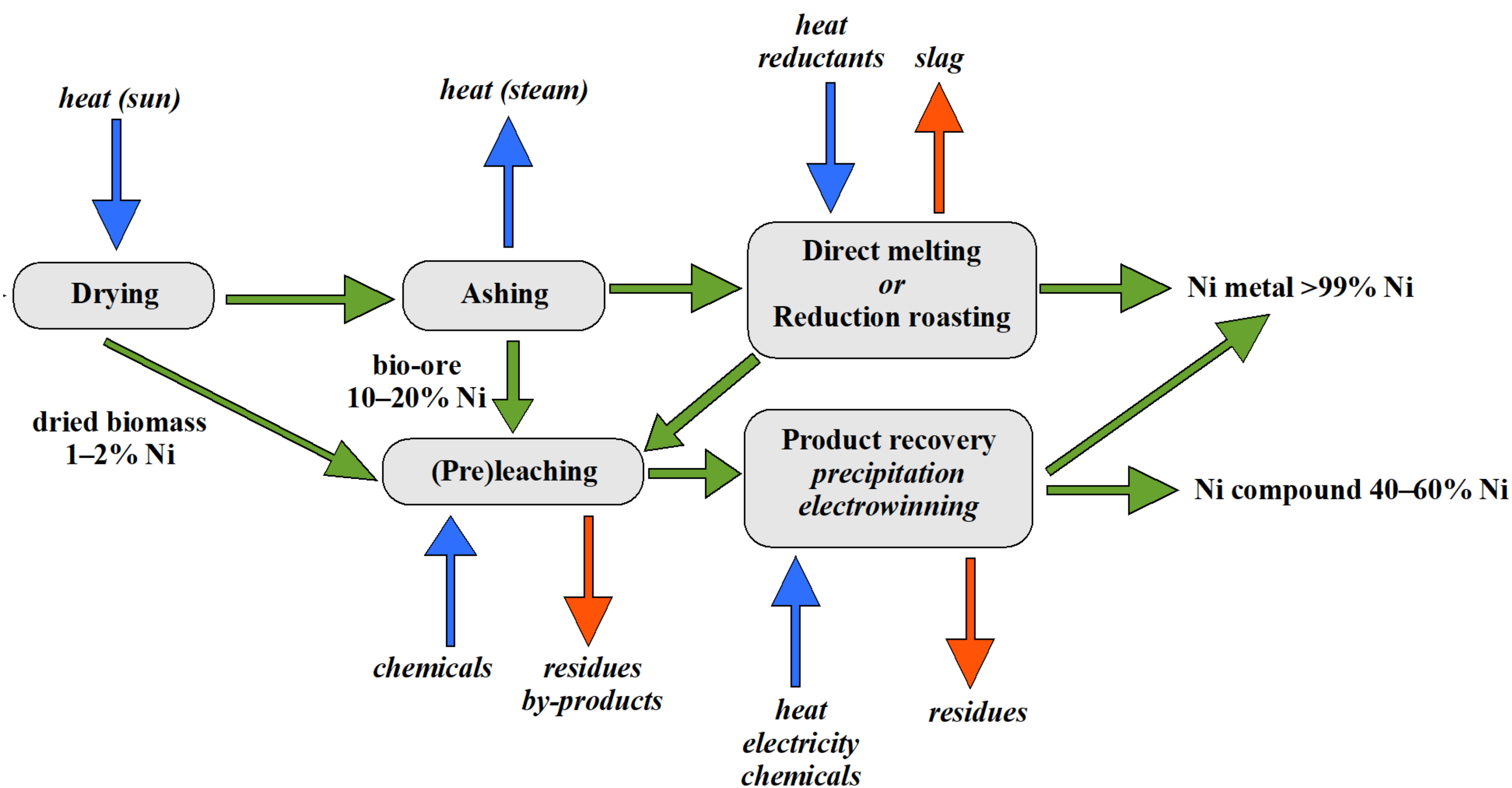
# Processing of nickel bio-ores

- The raw bio-ore produced from experimental phytomining has been processed via an arc furnace to produce nickel metal.
- Alternatively, the bio-ore is compatible as feedstock for major nickel hydrometallurgical plants.
- The high purity of the bio-ore also makes it uniquely suited to produce nickel catalysts for industrial synthetic organic chemistry, or converted into high value nickel chemicals for use in the electroplating industry.



# Processing of nickel bio-ores

- After harvesting  and drying the biomass contains1–2% nickel.
- The ashed biomass (= bio-ore) generally has 15–30 wt% nickel and is essentially free of major unwanted elements such as iron, silica and magnesium.
- Washing and selective precipitation has successfully demonstrated to obtain high purity nickel salts.


heat (sun)
heat (steam)
heat
reductants
slag
Drying
Ashing
Direct melting
or
Reduction roasting
Ni metal >99% Ni
bio-ore
10–20% Ni
dried biomass
1–2% Ni
(Pre)leaching
Product recovery
precipitation
electrowinning
Ni compound 40–60% Ni
chemicals
residues
by-products
heat
electricity
chemicals
residues

# Outlook

- Two decades after its inception and numerous successful experiments, commercial phytomining has not yet become a reality.

- This highlights the need to further encourage industry to apply new technologies that have the potential to improve mine site rehabilitation while providing opportunities for sustainable post-mining livelihoods, especially in tropical regions.

- To build the case for the minerals industry, a large-scale demonstration is needed to identify operational risks and provide 'real-life' evidence for profitability.

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Australia
CREATE CHANGE

# Sustainable Minerals Institute

Responsible resource development in the 21st century

# Create change for a better world

The University of Queensland
Australia
CREATE CHANGE

Unlocking Complex Orebodies

Transforming Mine Lifecycles

Digital Mine

Organisation Governance and Leadership

Transformational Learning

Health and Safety

Social Responsibility

Water Management

Land Rehabilitation

Mining and Metallurgy

Geology

# Thank you

Sustainable Minerals Institute
smi@uq.edu.au

Professor Neville Plint

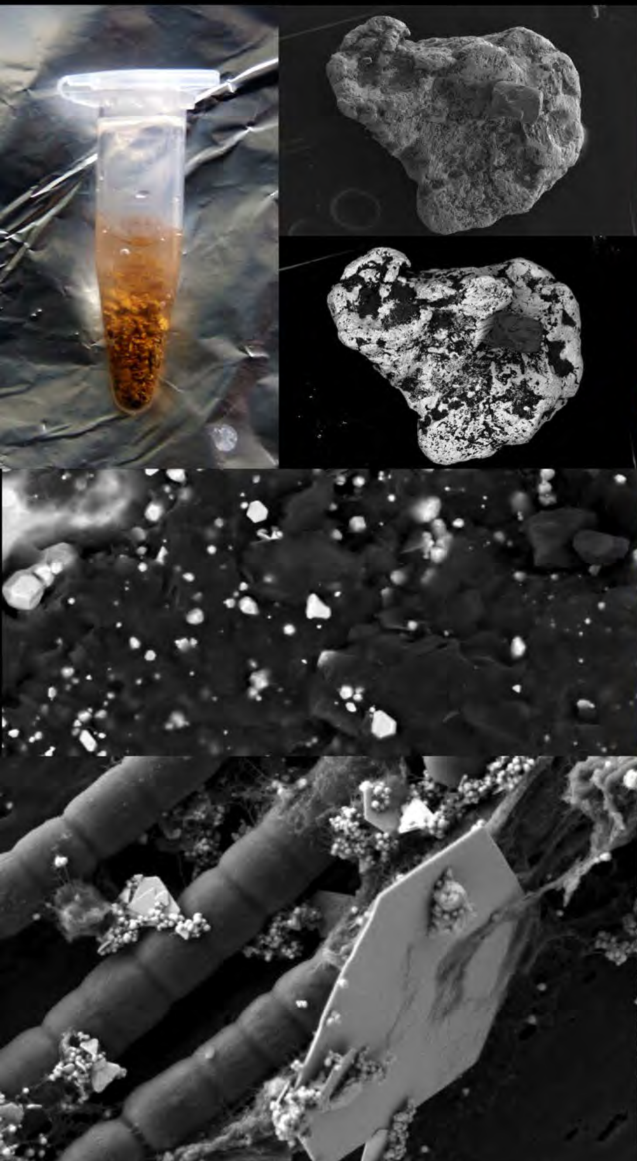
Director

@SMI_UQ

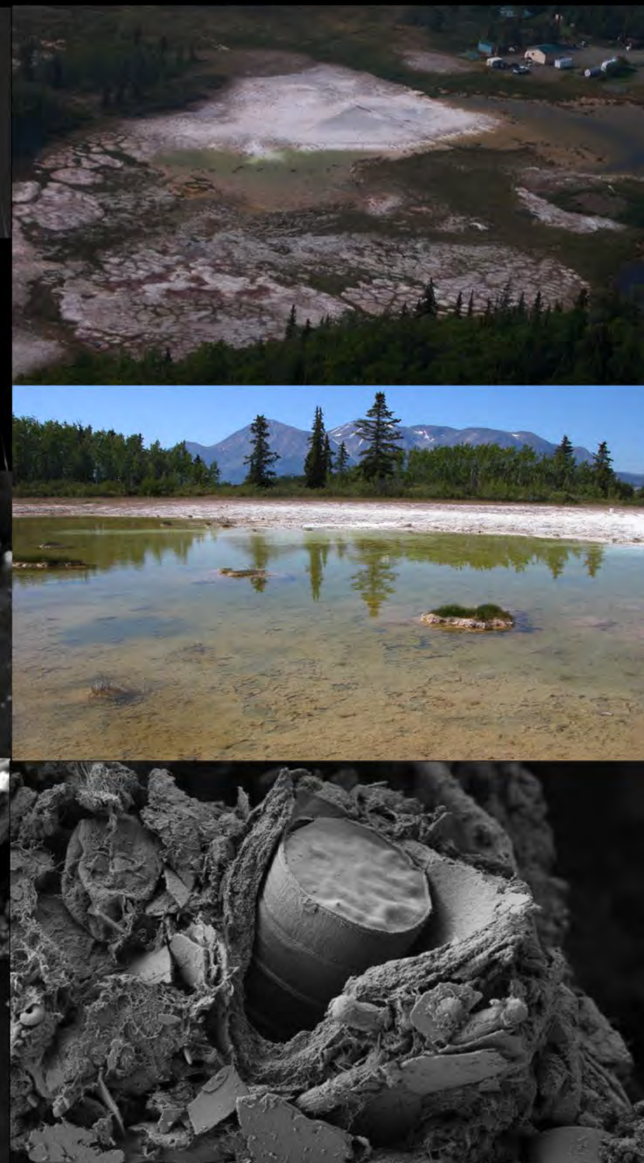
**Sustainable Minerals Institute**

N.Plint@uq.edu.au

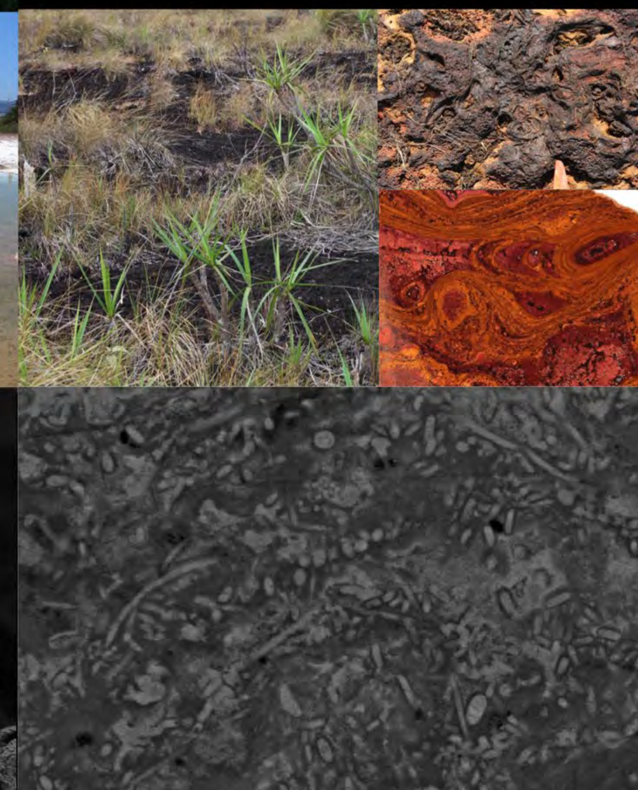
The biogeochemical cycling of gold needs to be targeted in exploration.



Mineral carbonation can be accelerated by microbial activity.



Biotechnology can be used for the stabilization of iron mine waste



# Geomicrobiology and AMD

G. Southam

(Heike Bostelman, John Dockrey, Steve Enders, Anicia Henne, Chris Knickerbocker, Liane Loiselle, Randy Mielke, Jeremiah Shuster)

School of Earth & Environmental Sciences

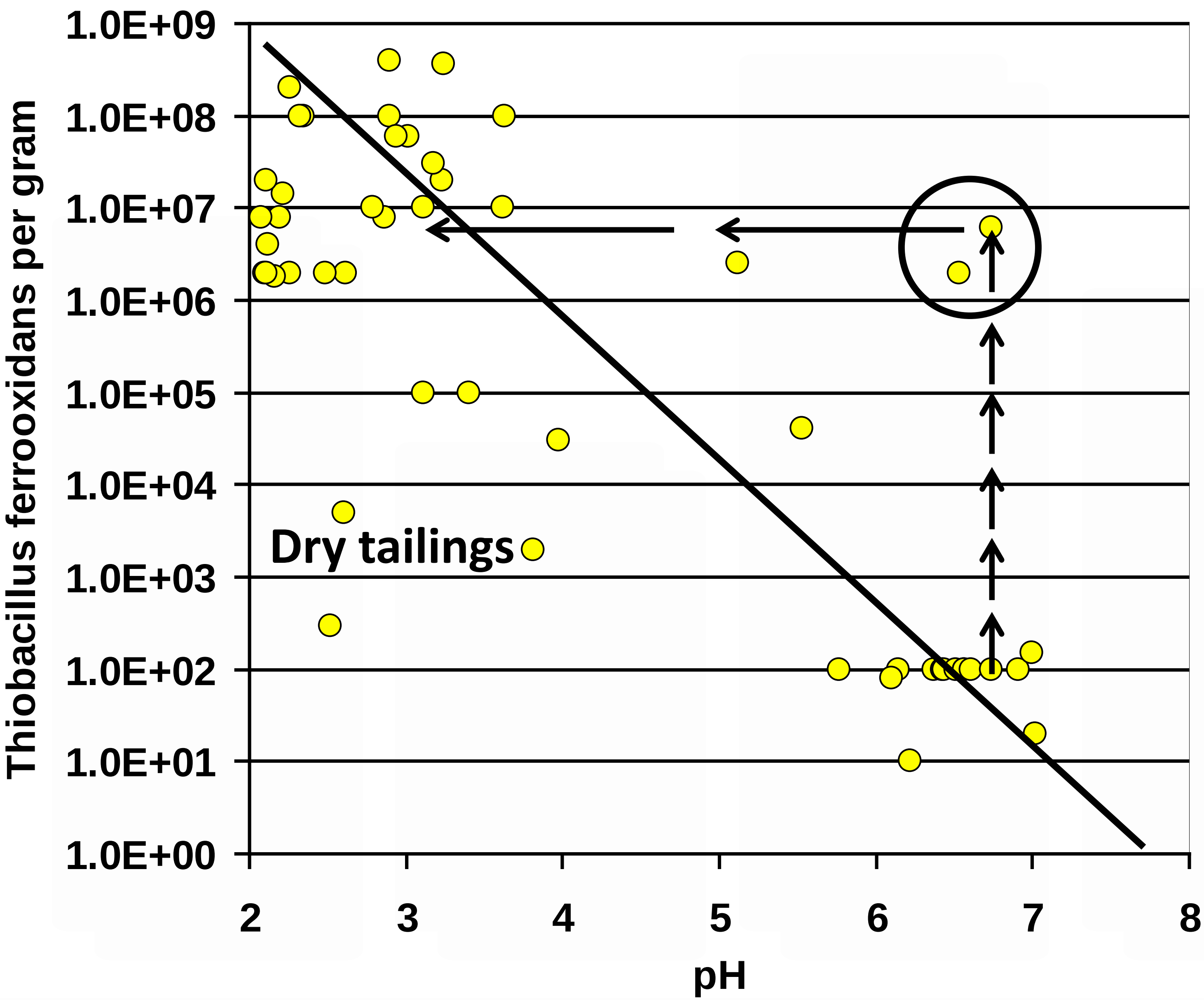
The University of Queensland

Lemoine Mine, Quebec, Canada

$Fe^{2+} + \frac{1}{4}O_2 + H^+ \rightarrow Fe^{3+} + \frac{1}{2}H_2O$; Singer and Stumm, 1970

$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

Singer, P.C. and W. Stumm. 1979. Acidic Mine Drainage: The Rate-Determining Step. Science 167: 1121-1123

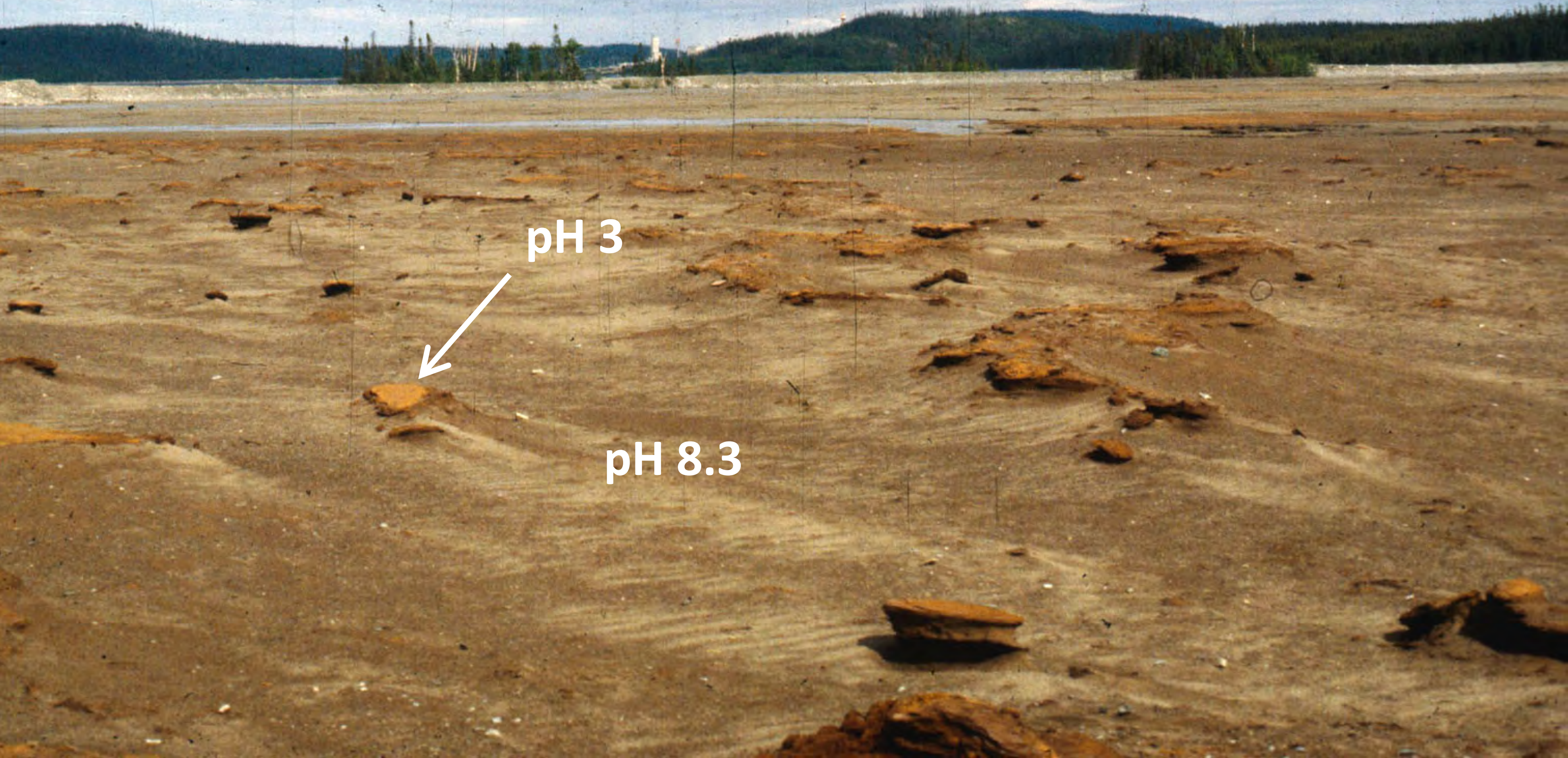

1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
Thiobacillus ferrooxidans per gram
Dry tailings
2
3
4
5
6
7
8
pH

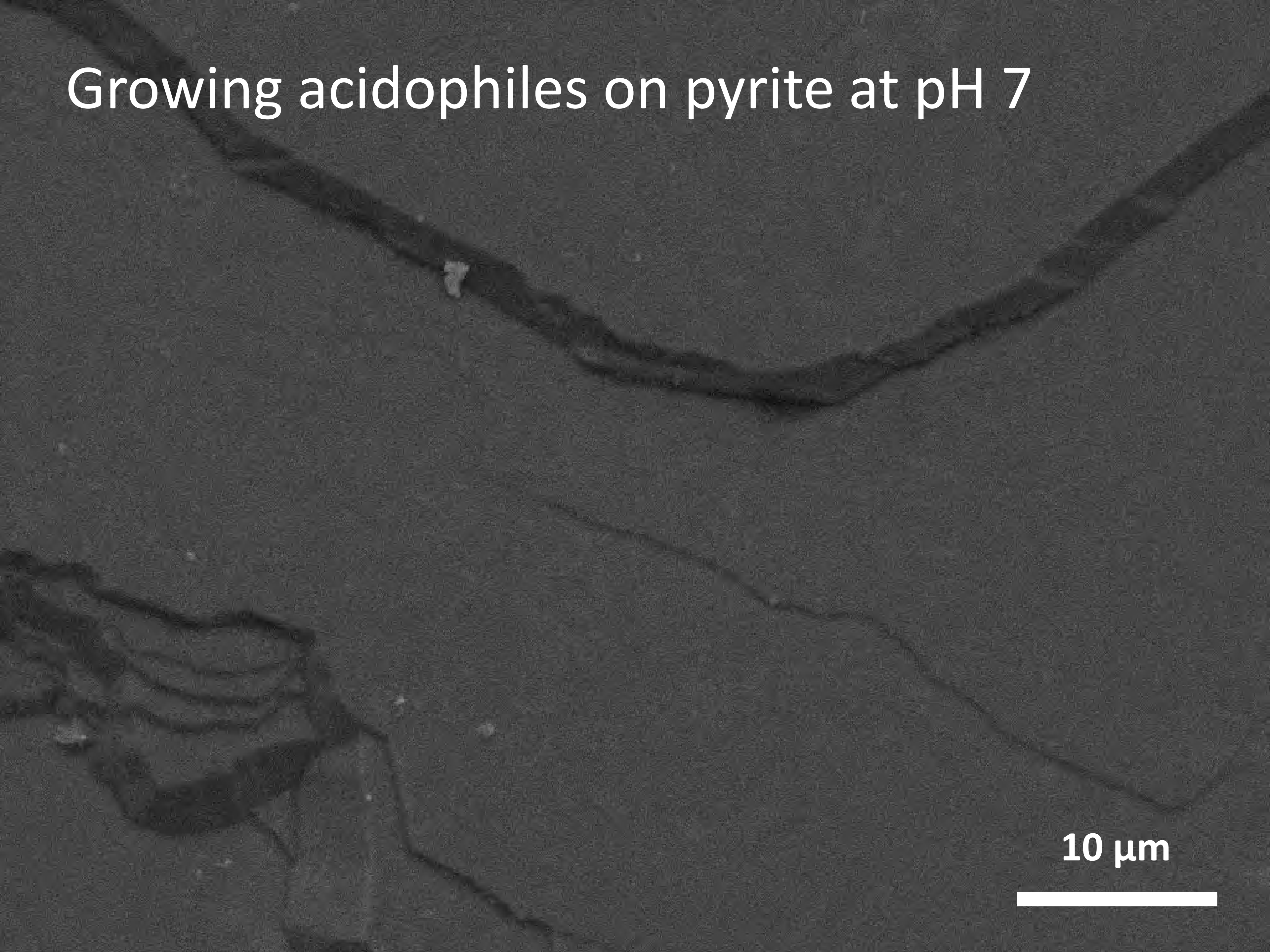
## Copper Rand Mine, Quebec, Canada; pH 8.3

$$Fe^{2+} + \frac{1}{4}O_2 + H^+ \rightarrow Fe^{3+} + \frac{1}{2}H_2O$$

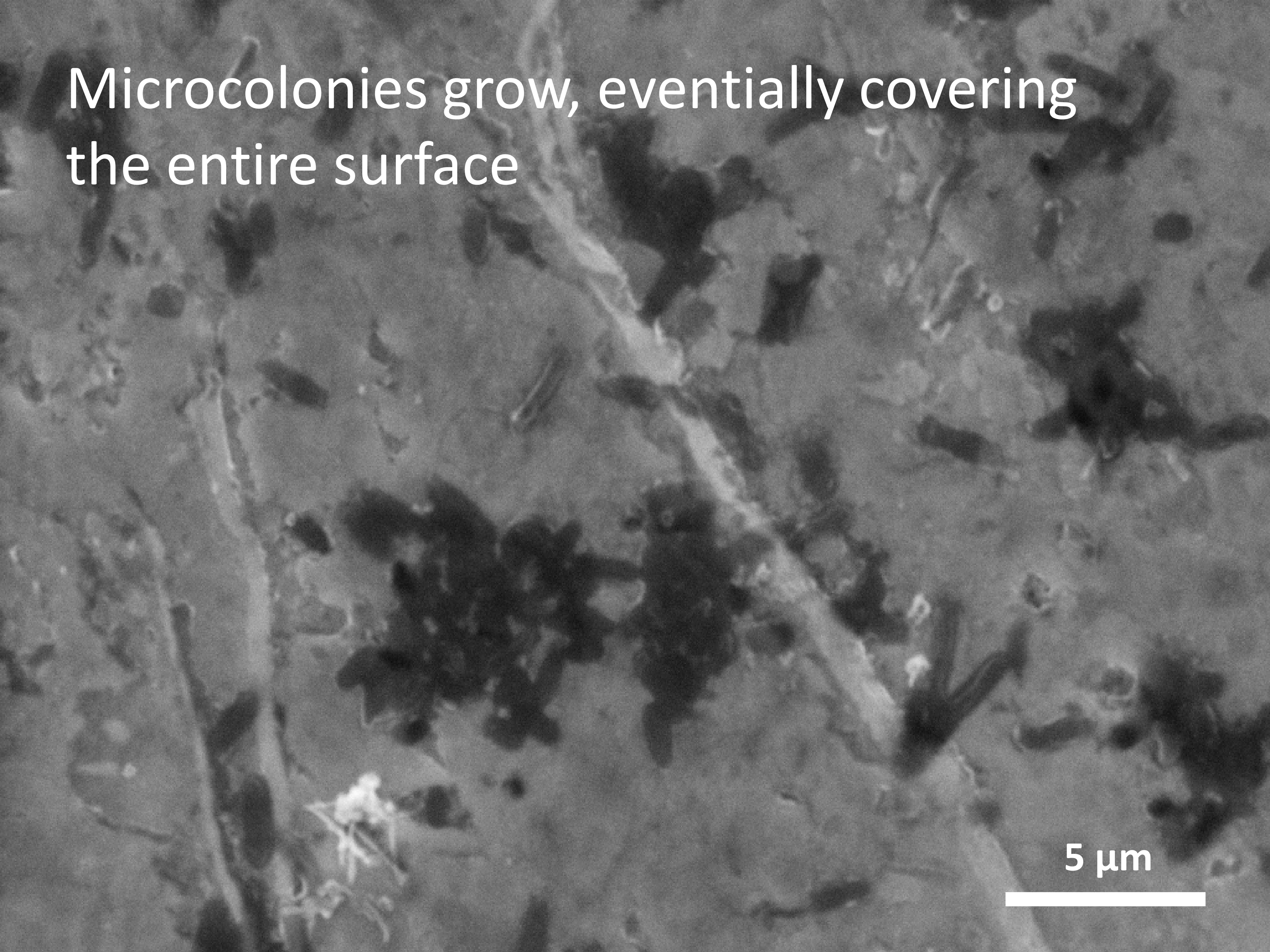
$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_{3(s)}$$

$$\cancel{FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+}$$




Growing acidophiles on pyrite at pH 7
10 µm

# Phosphate adsorbs to pyrite; *A. ferrooxidans* binds to phosphate

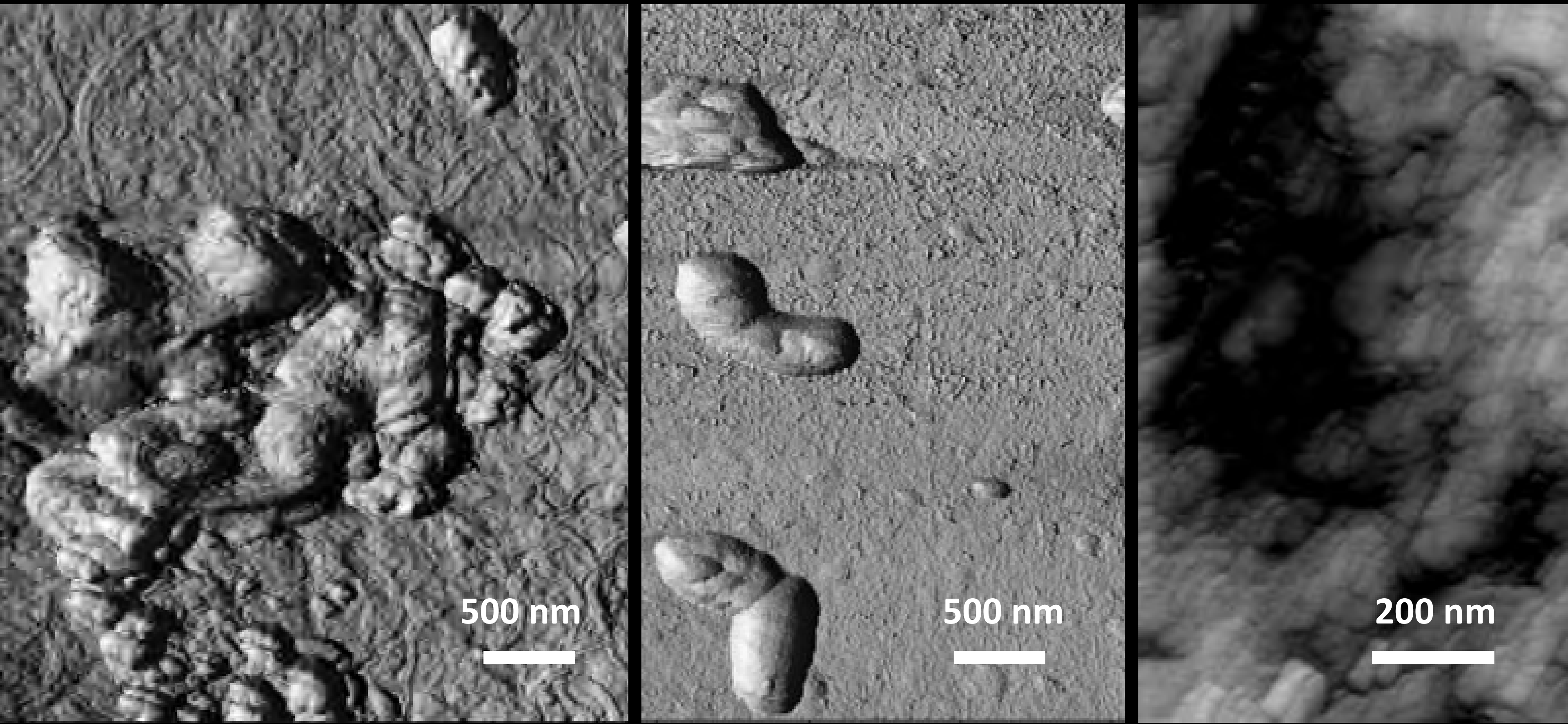

Microcolonies grow, eventially covering the entire surface
5 µm

Live is green / red is dead

*A. ferrooxidans* in the water die

*A. ferrooxidans* on pyrite live

# Biooxidation of pyrite ($FeS_2$) at pH 7



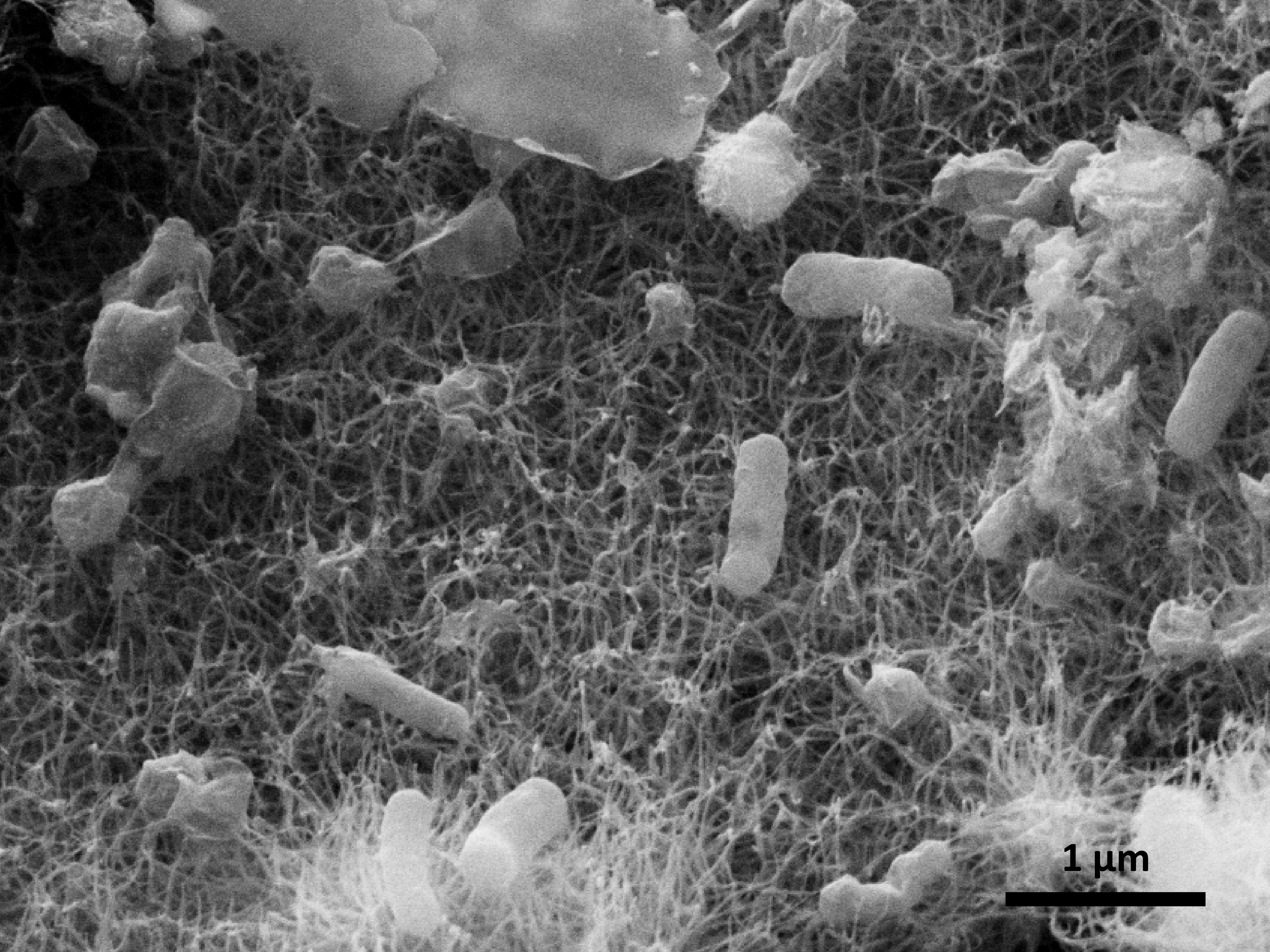

$$Fe^{2+} + \frac{1}{4}O_2 + H^+ \longrightarrow Fe^{3+} + \frac{1}{2}H_2O$$

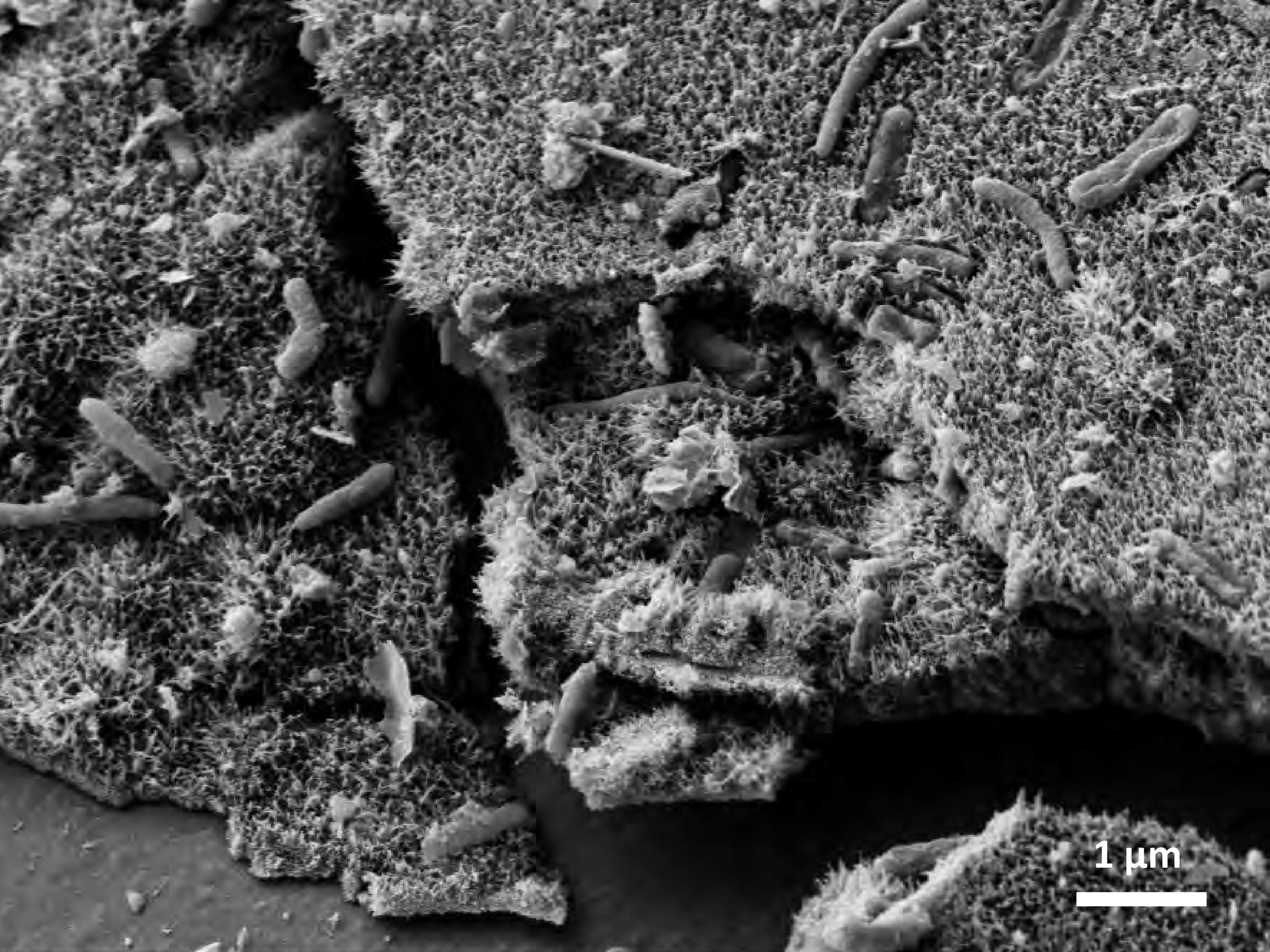
$$FeS_2 + 14Fe^{3+} + 8H_2O \longrightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

# The Antamina mine; the importance of corrosion-biofilms


Pyrite @ pH 7; corrosion-biofilm
40 µm


5 µm

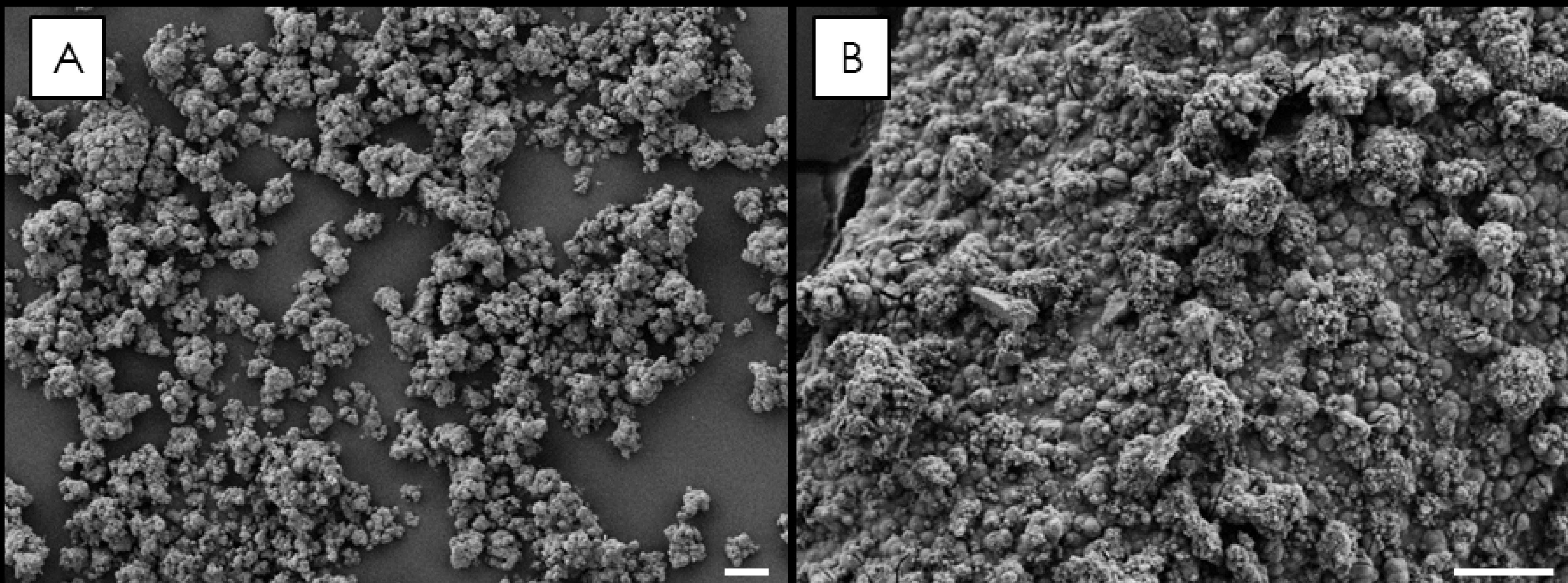

1 µm


1 µm

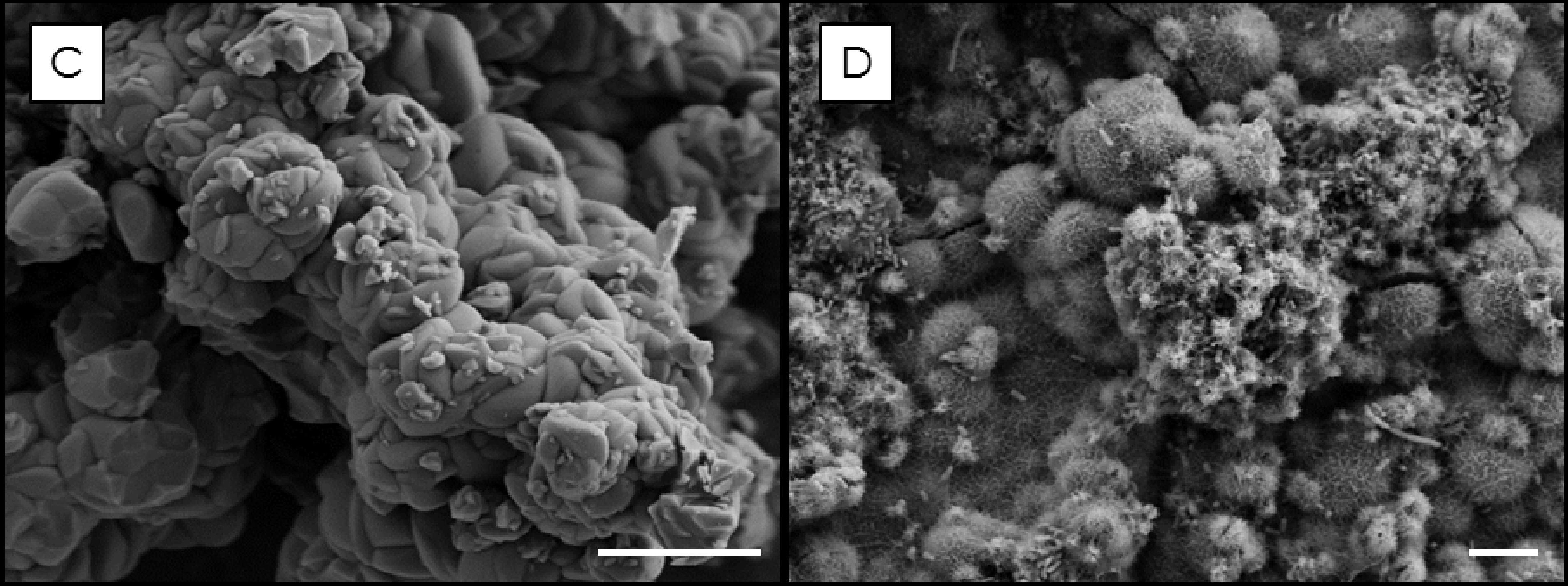
# Minas de Riotinto; INAP member since… (the 8th Century BC?)


Rio Tinto

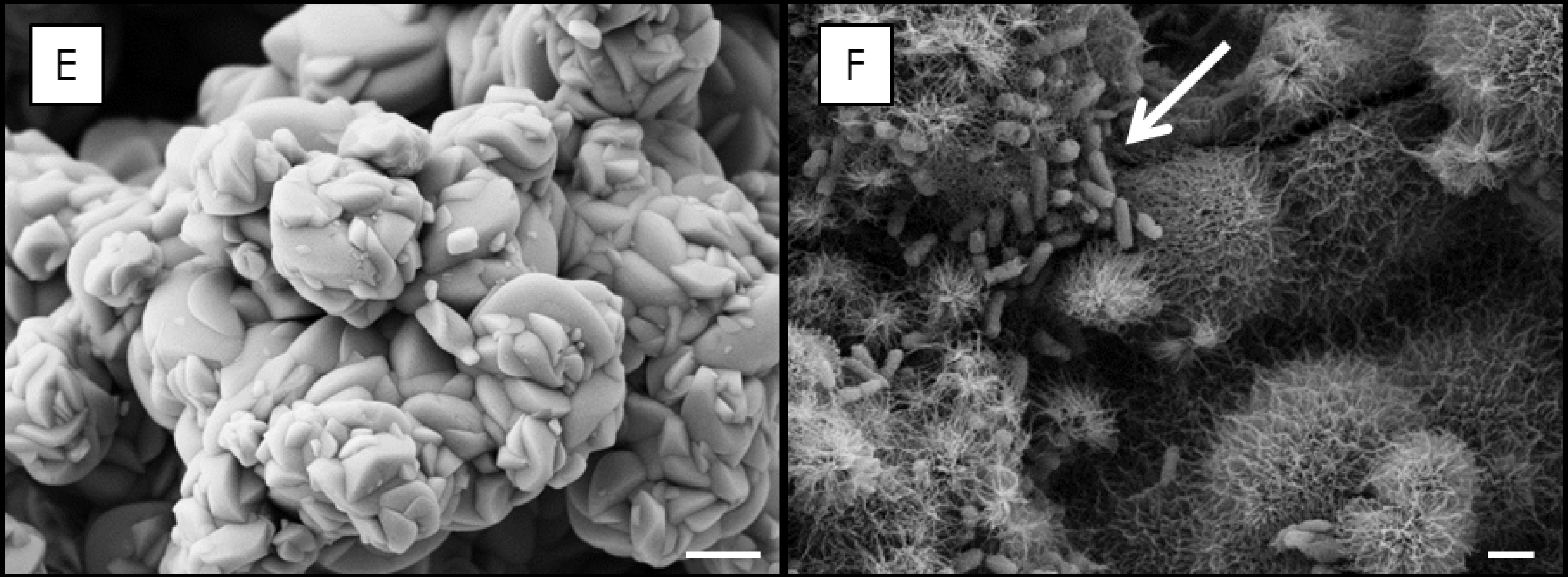
# Abiotic (A) versus Biotic (B) jarosite (10 μm size bars)

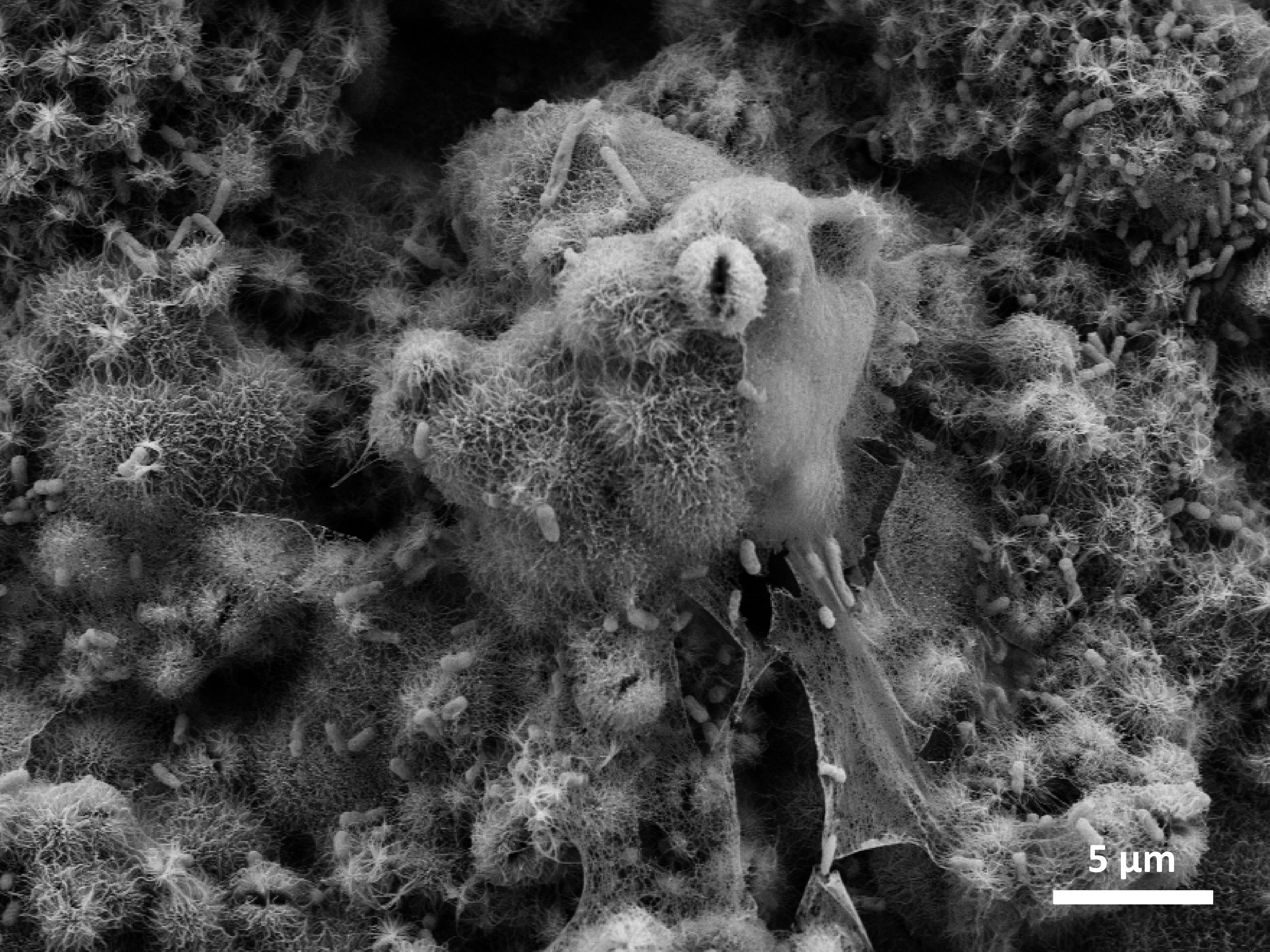


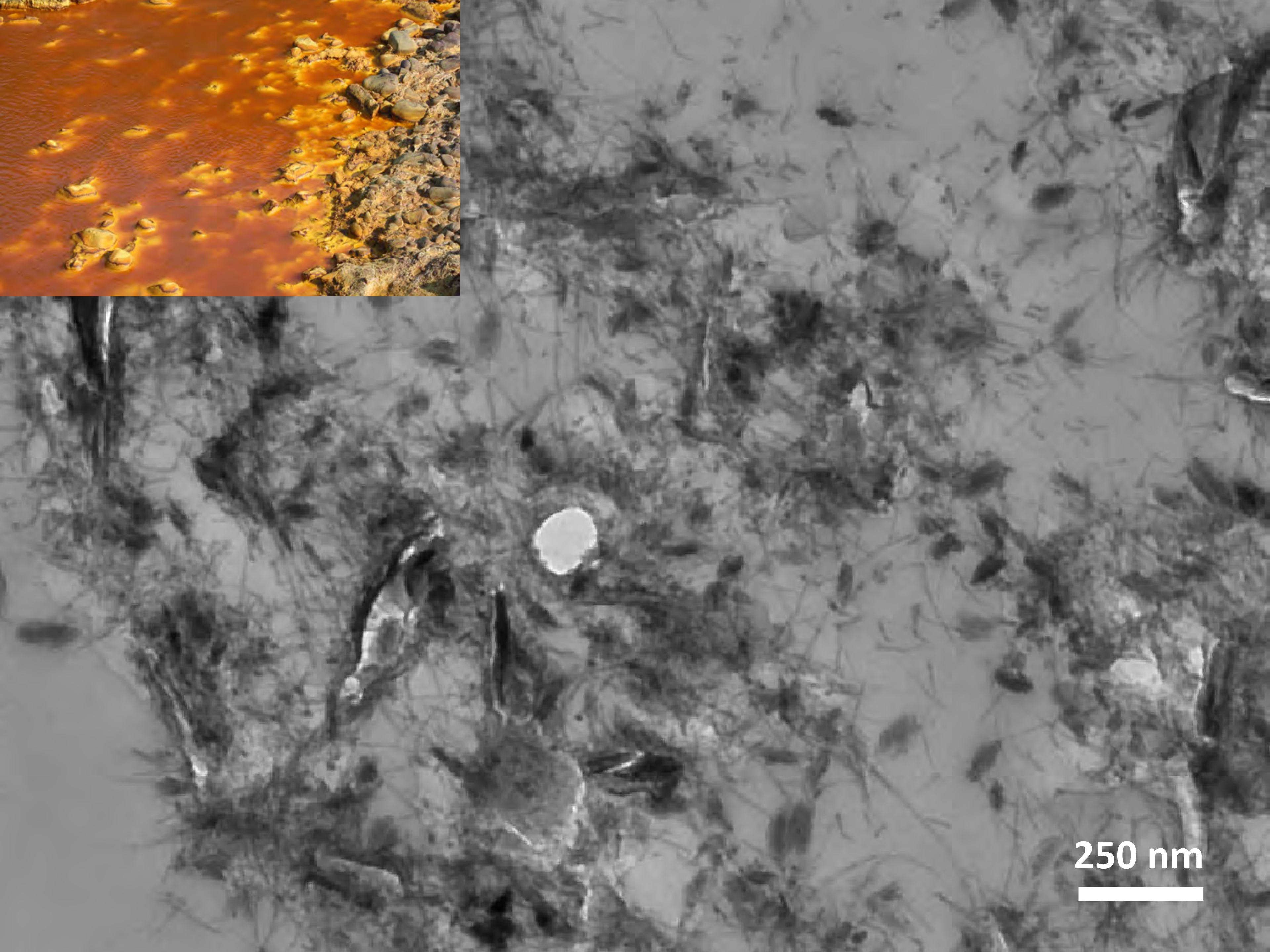
# Abiotic (A) versus Biotic (B) jarosite
# (5 µm size bars)

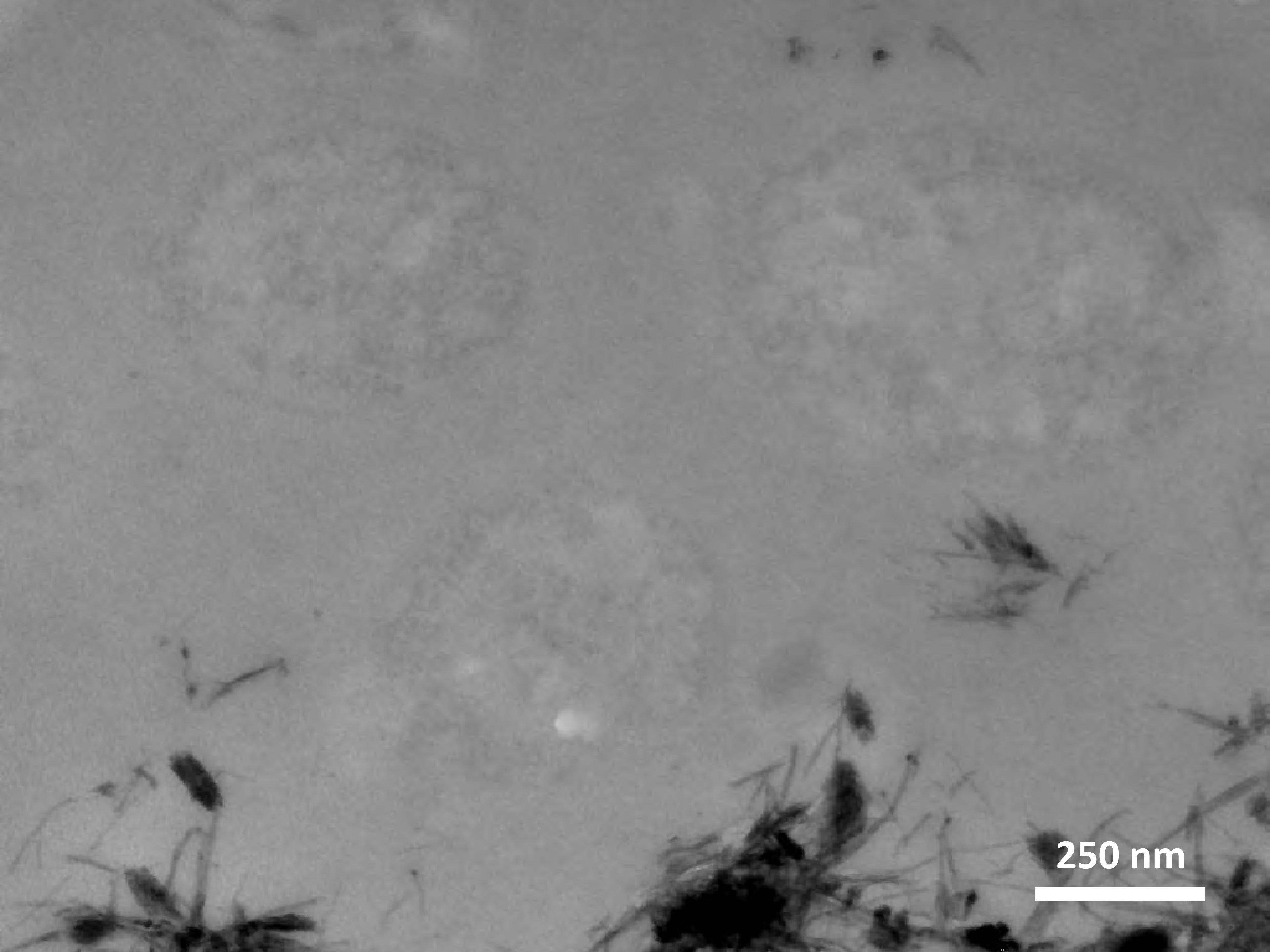


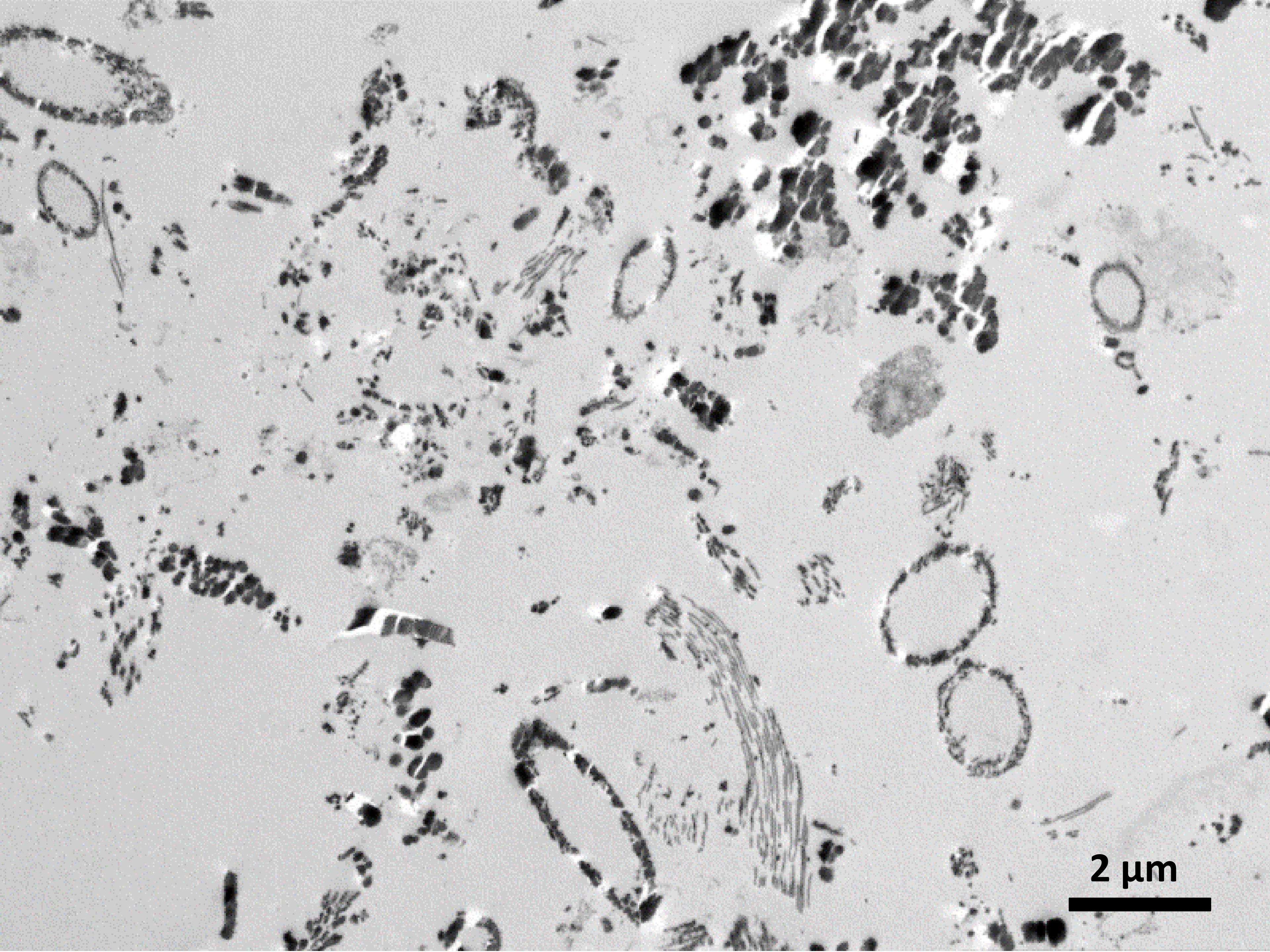
# Abiotic (A) versus Biotic (B) jarosite
# (1 µm size bars)




5 µm

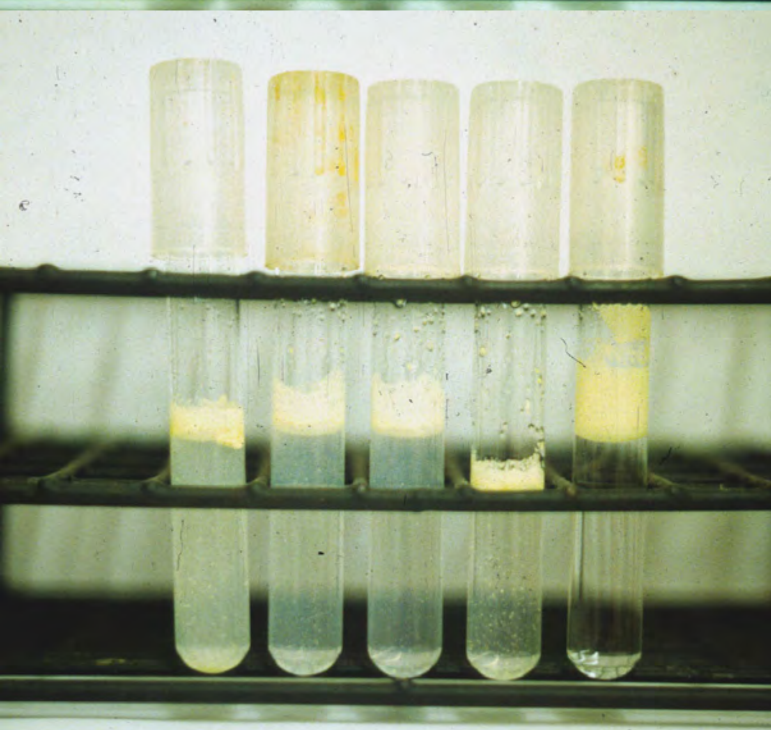

250 nm

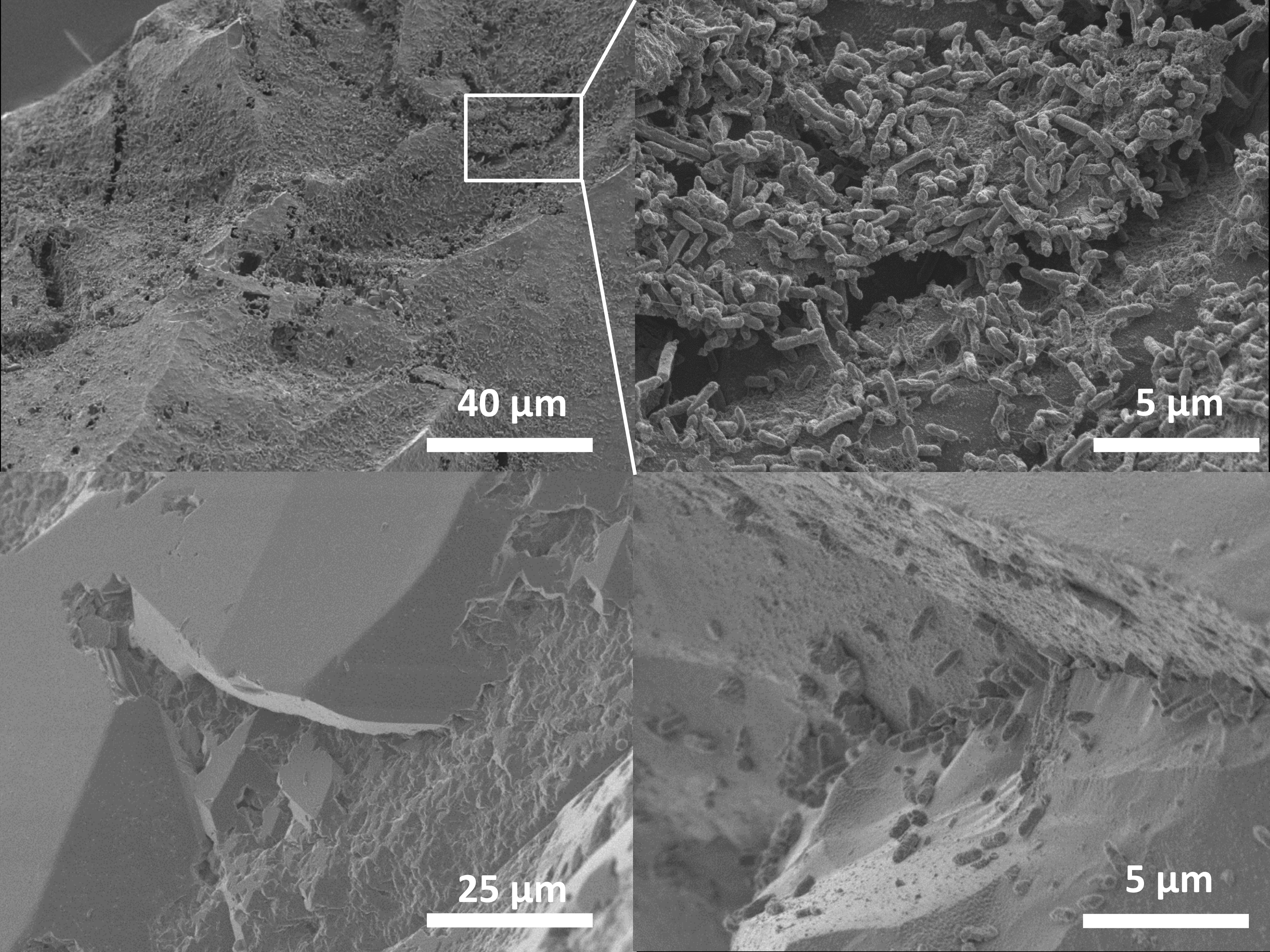

250 nm

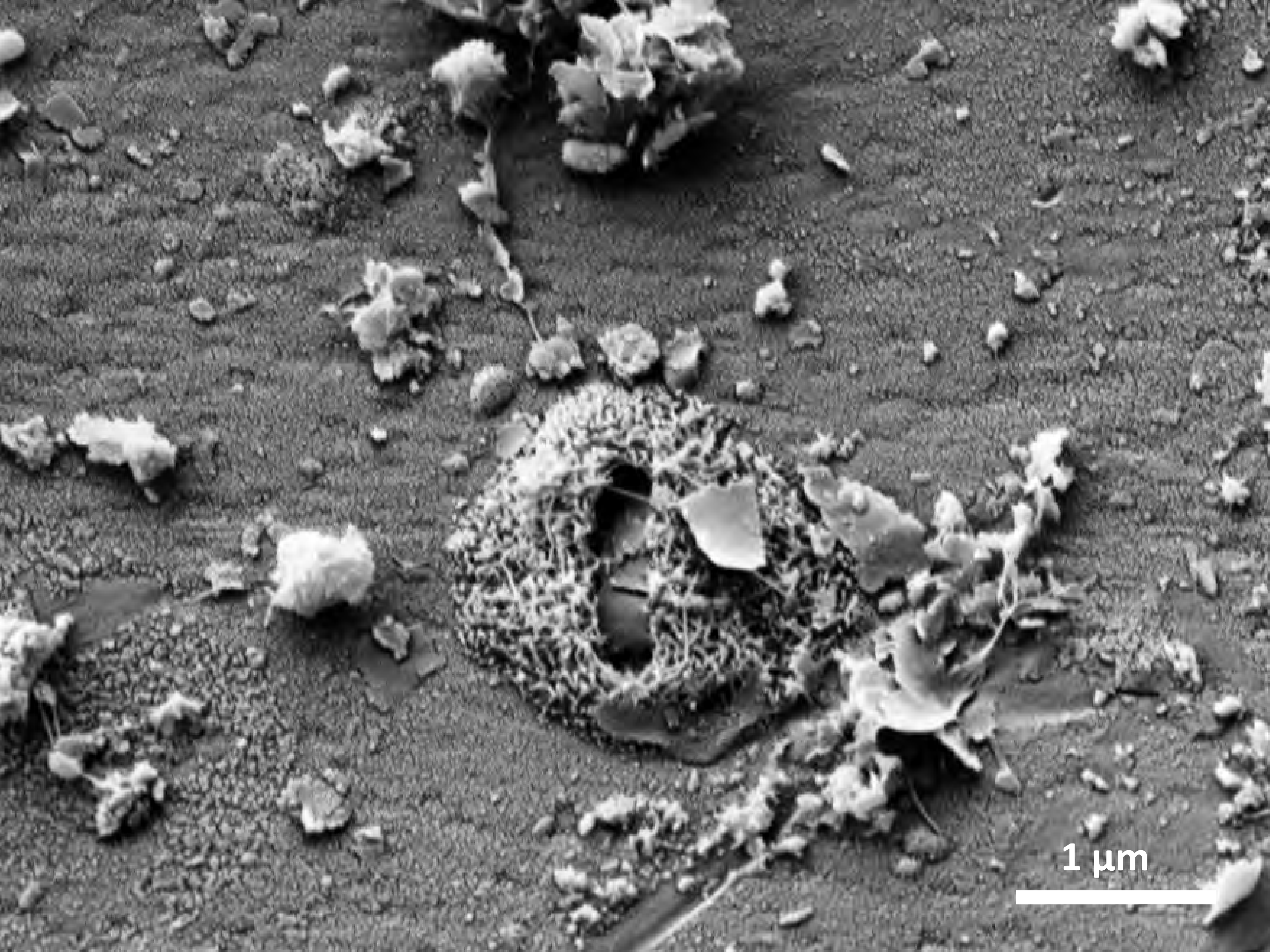

2 µm

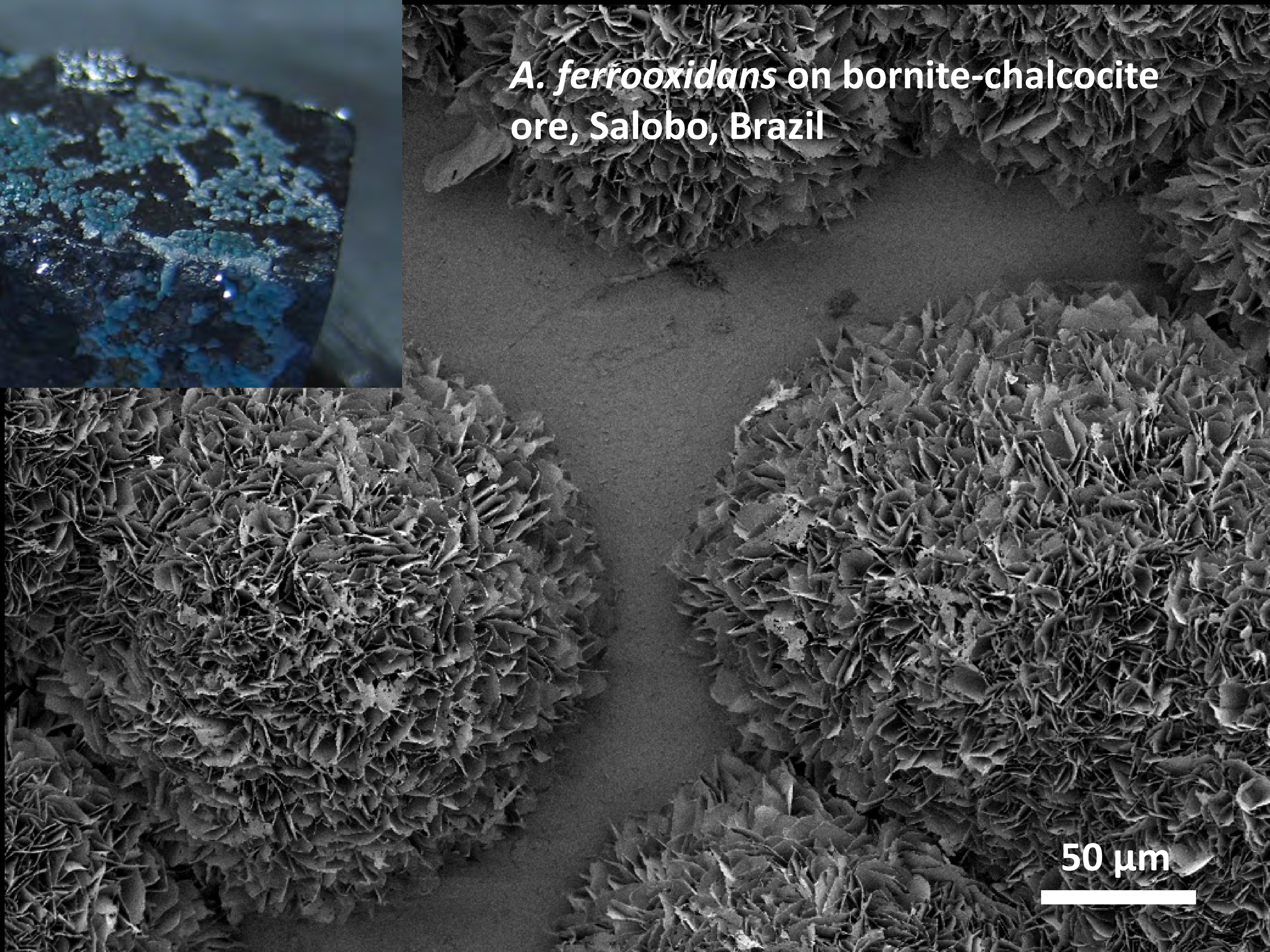

The Morenci Mine, a world-class supergene
Cu system; 400 tonnes Cu/d bioleaching

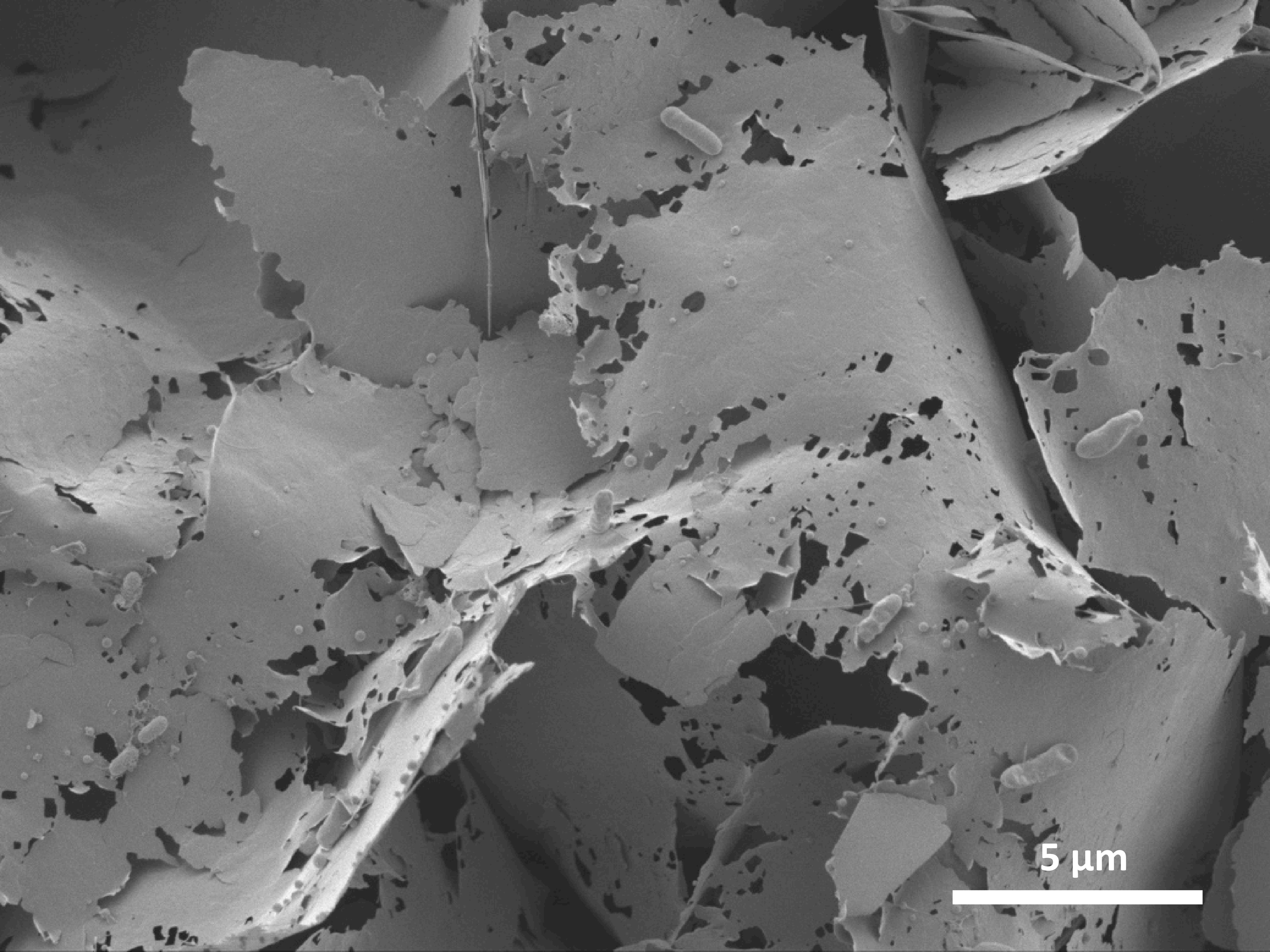

Enders et al., 2006. Econ.
Geol. 101:59-70.

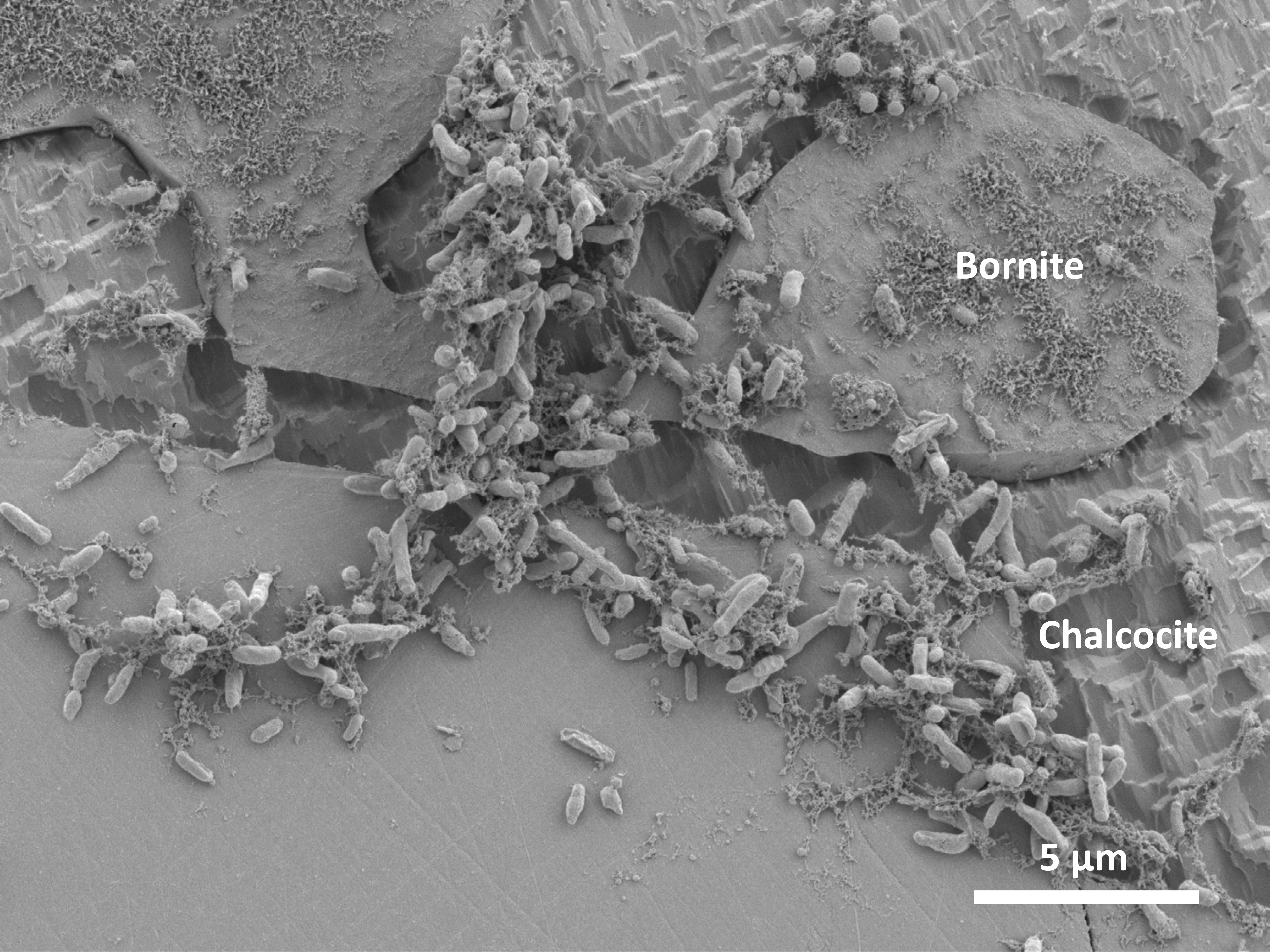


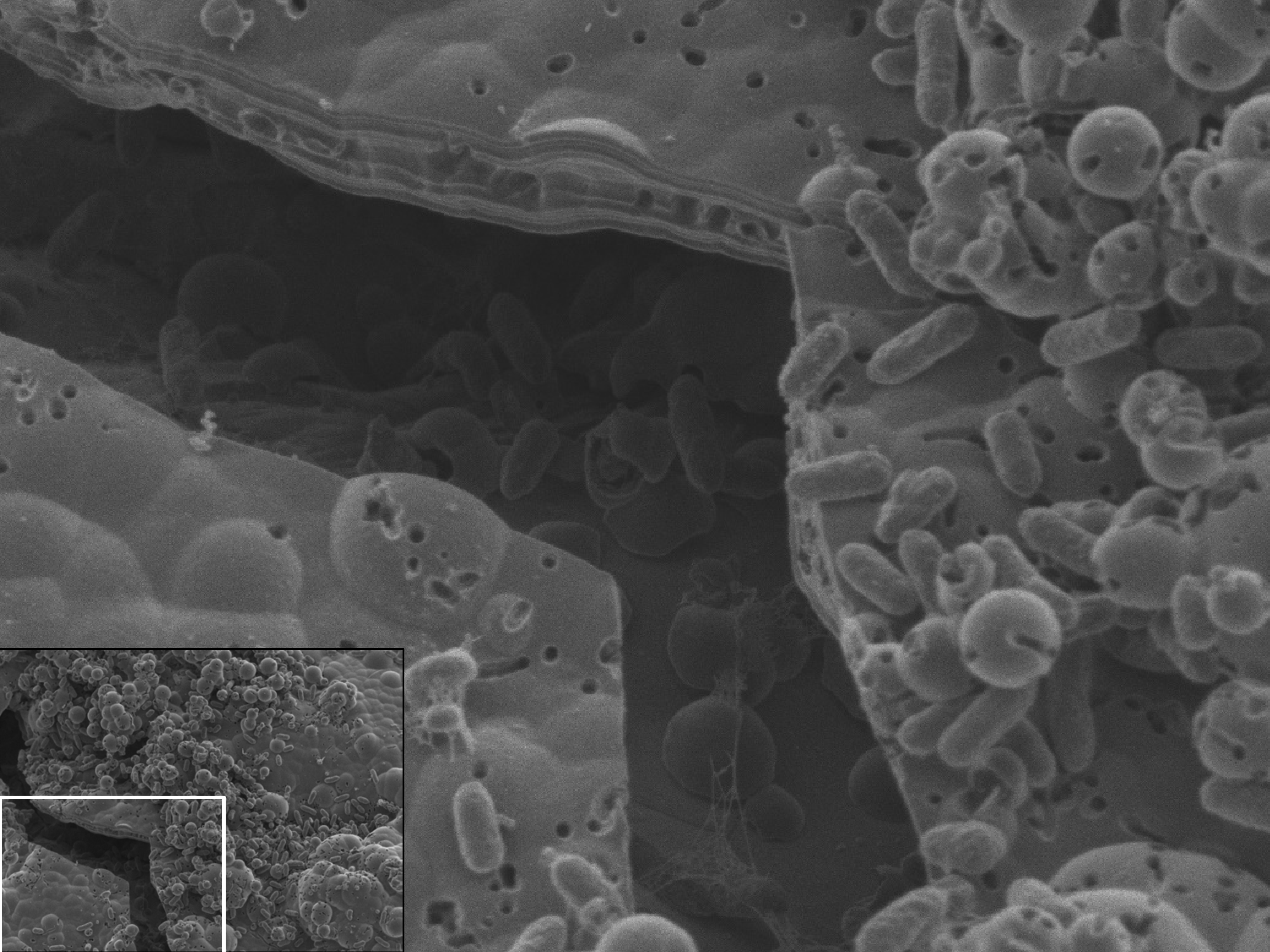

40 µm
5 µm
25 µm
5 µm

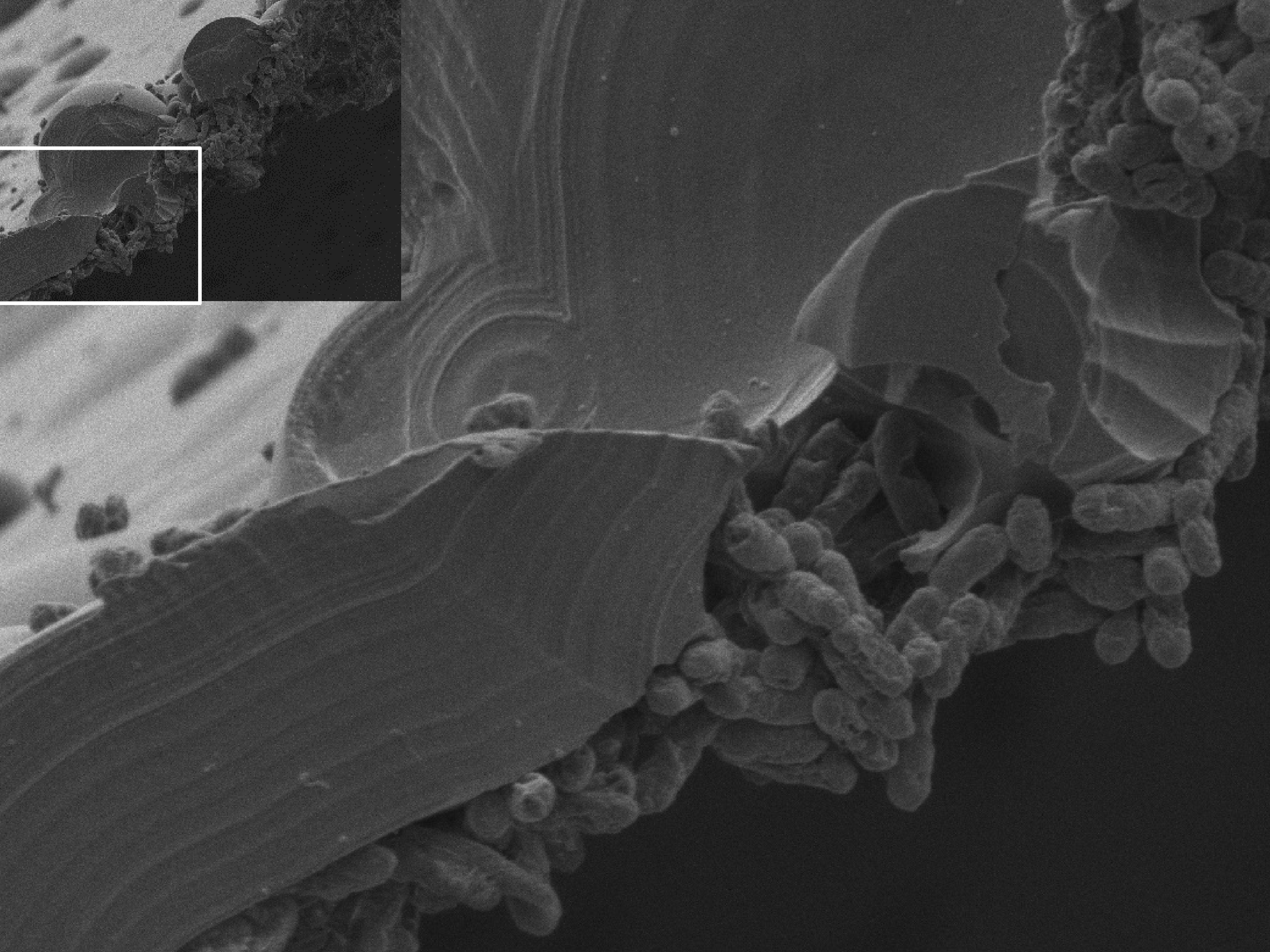

1 µm


*A. ferrooxidans* on bornite-chalcocite ore, Salobo, Brazil
50 µm

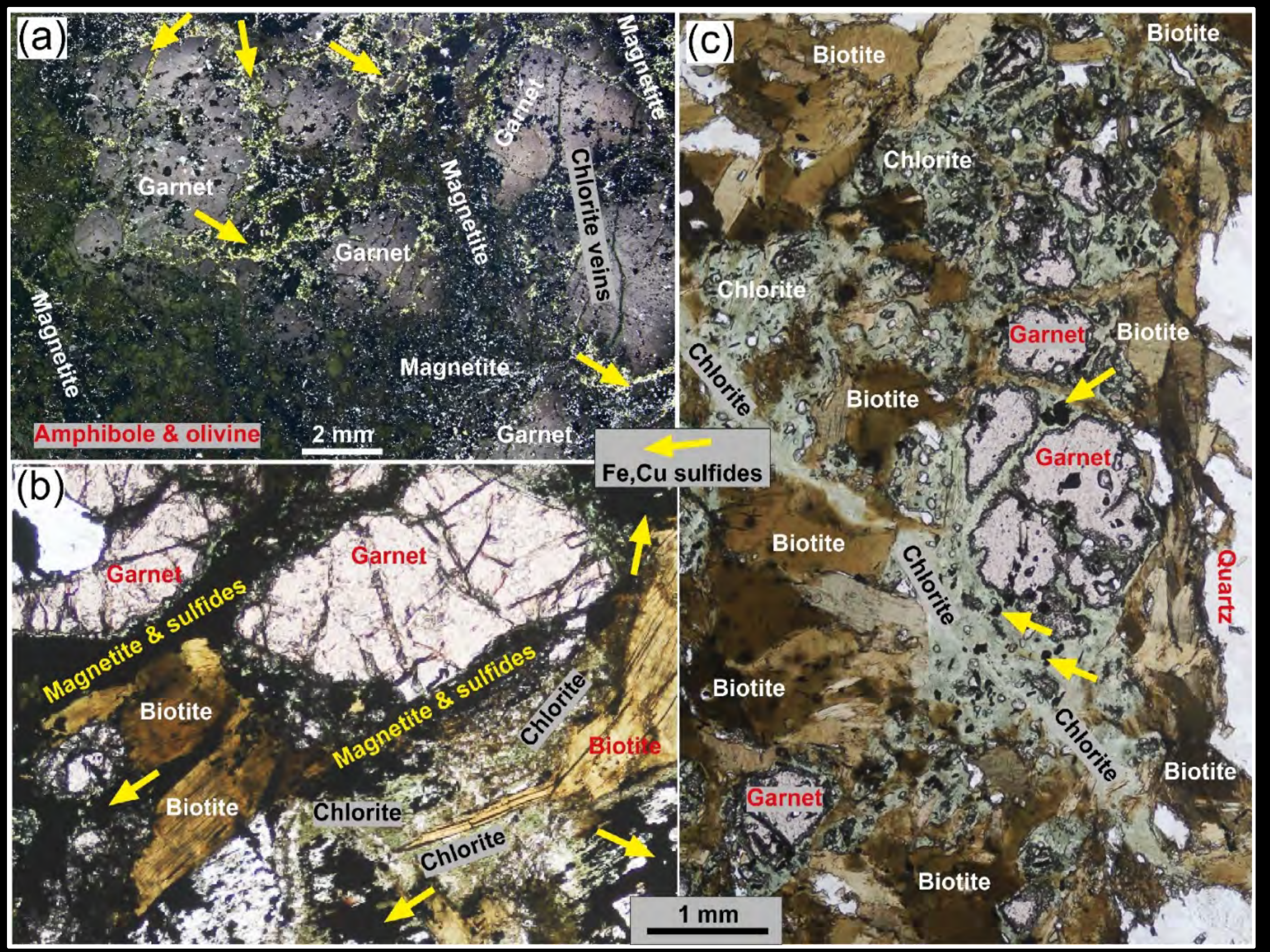

5 µm

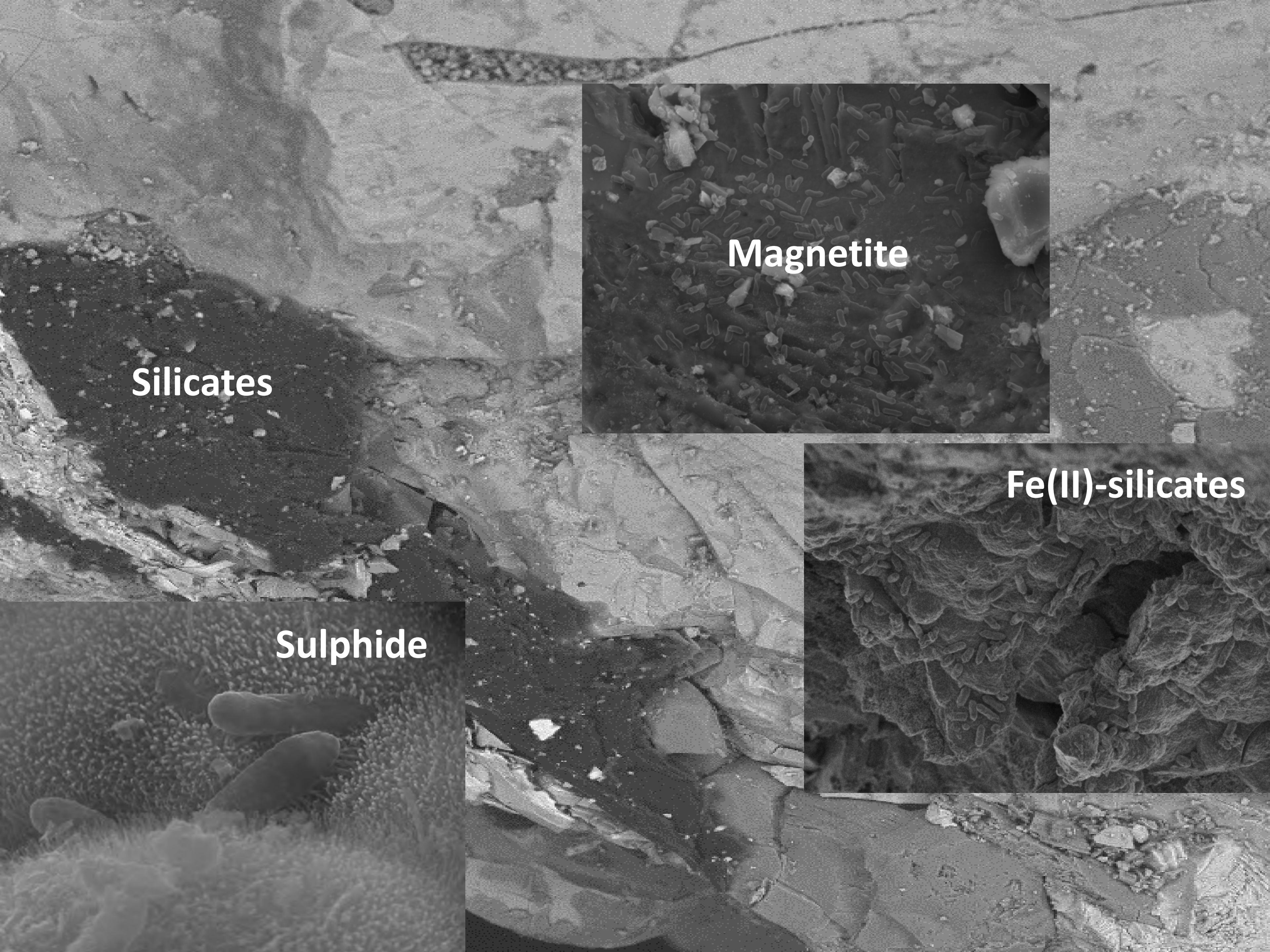

Bornite
Chalcocite
5 µm

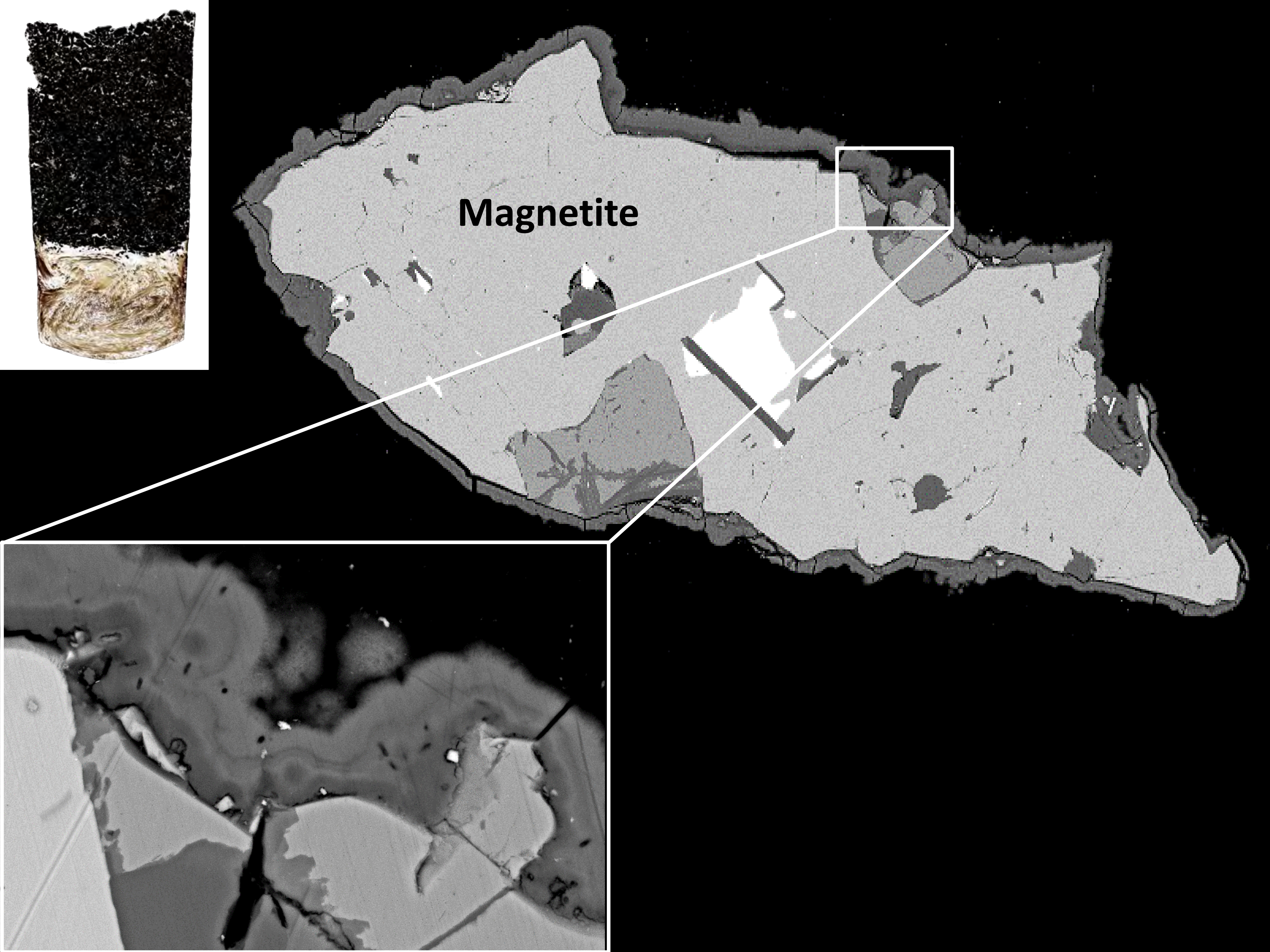




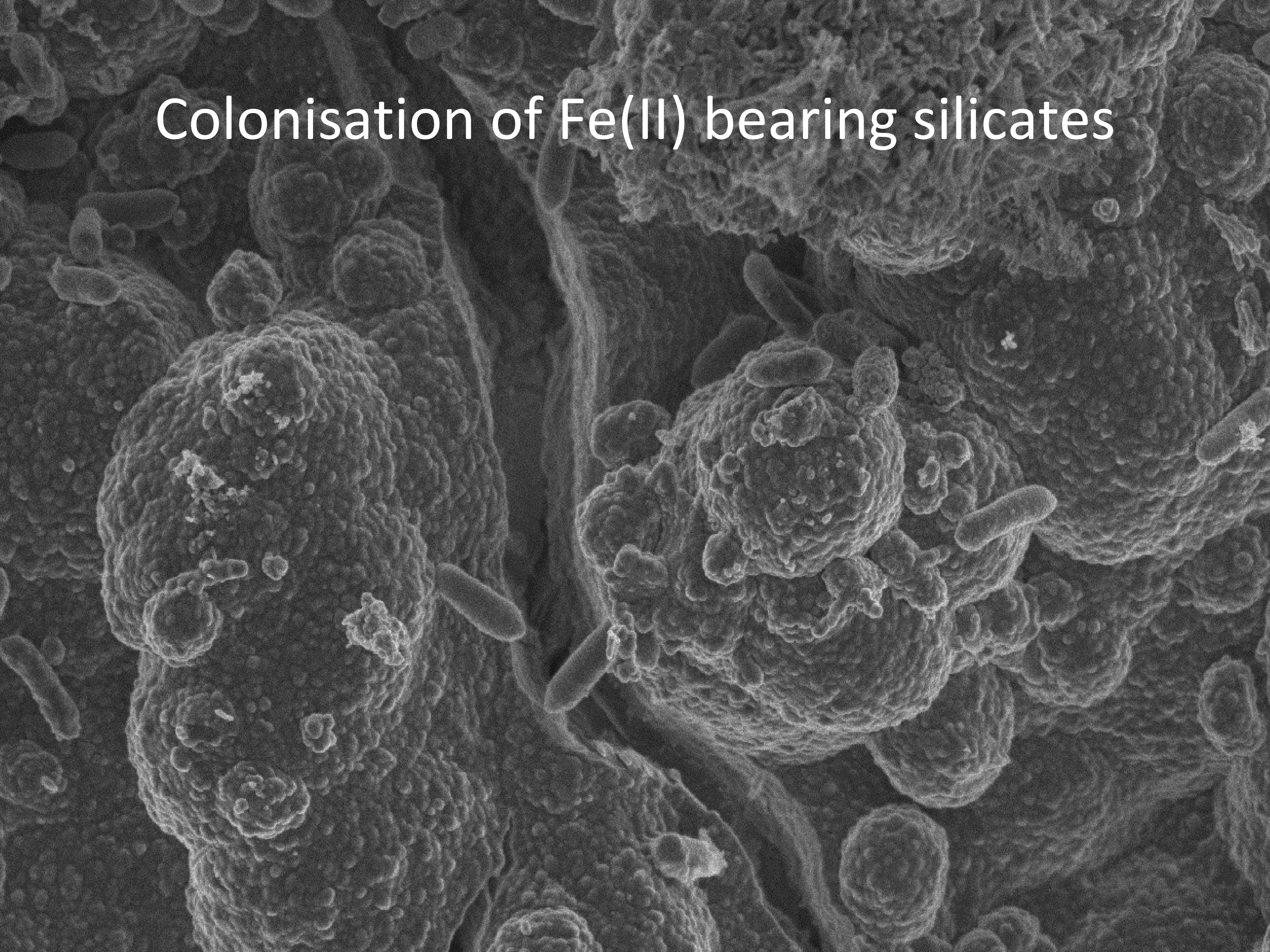
# Salobo Mine


(a)
Garnet
Garnet
Garnet
Garnet
Garnet
Magnetite
Magnetite
Magnetite
Magnetite
Chlorite veins
Amphibole & olivine
2 mm
Fe,Cu sulfides
(b)
Garnet
Garnet
Magnetite & sulfides
Magnetite & sulfides
Biotite
Biotite
Biotite
Chlorite
Chlorite
Chlorite
(c)
Biotite
Biotite
Chlorite
Chlorite
Chlorite
Chlorite
Chlorite
Garnet
Garnet
Garnet
Biotite
Biotite
Biotite
Biotite
Biotite
Biotite
Quartz
1 mm


Magnetite
Silicates
Fe(II)-silicates
Sulphide


Magnetite

# Colonisation of Fe(II) bearing silicates




Life finds a way