PART 2

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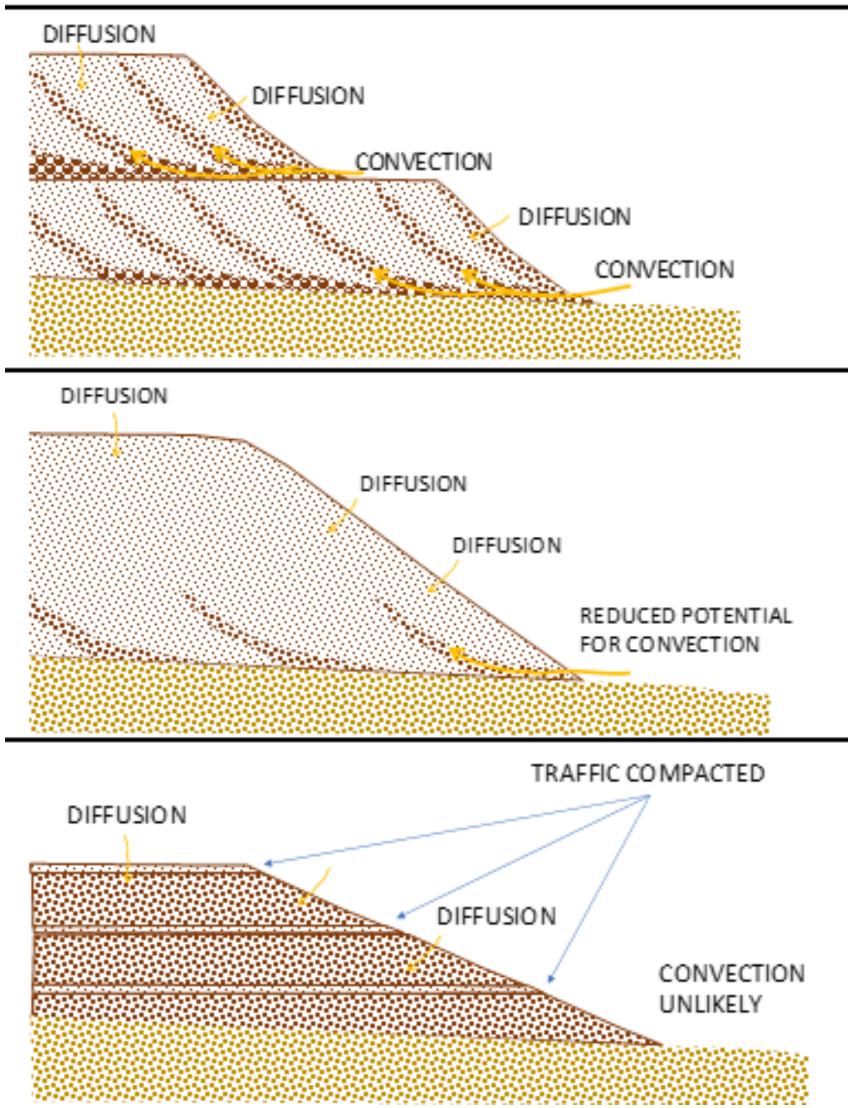
Topics

- The future of tailings and waste rock management
  - Focus on waste rock – building better WRDs
  - A future without standalone above-grade wet slurry TSFs
  - Combining Rock & Tailings - Commingling
- Integrated Mine Planning and ARD Waste Management
- Characterisation/Prediction – New Approaches/Challenges
- Treatment- incl Microbiological
- Pit Lakes
- A Regulator's Perspective
- Emerging Topics (CO_2 from waste, Li, REEs etc)

Building Better WRDs

- Waste Rock Dump Assessment – A Garvie et al
  - *Modelling evolution of geochemical processes in WRDs at three mines – Iron Ore mine in Western Australia, a Metallurgical Coal mine in Queensland, and a Copper mine in Chile.*
  - *effects of WRD construction methods, composition and climate on the generation of acid and metalliferous drainage (AMD)*
  - *focus on assessing beneficial outcomes from WRD construction methods (thin layer lifts) and active or passive surface compaction by traffic that may limit or prevent convection*
  - *clear benefit for the implementation of AMD control measures as part of WRD construction*

- Effects of Mine Rock Stockpile Construction Methodology on Metal Leaching and ARD Treatment Costs – M O'Kane et al
  - *Modelling comparison of 10 m lifts of sulfide mine rock with 1 m interim compacted oxide mine rock layers and a vegetated cover system, with a 'conventional' WRD constructed using 30 m lifts*
  - *96% decrease in lime requirements for ML-ARD treatment over 45 years for the 10m lift and interlayer compaction design*



Future Regulation – A Paradigm Shift?

- Currently "progressive rehabilitation" is most often viewed as being the final covered and revegetated landform – often with a cover system having been put in place after years of exposure, and generation of contained leachable oxidation products.
- Should ground-up construction methods (with compacted interlayers) be considered/assessed by regulators as a form of progressive rehabilitation in calculating (or refunding) a performance bond, since this is a method of source control from the beginning?

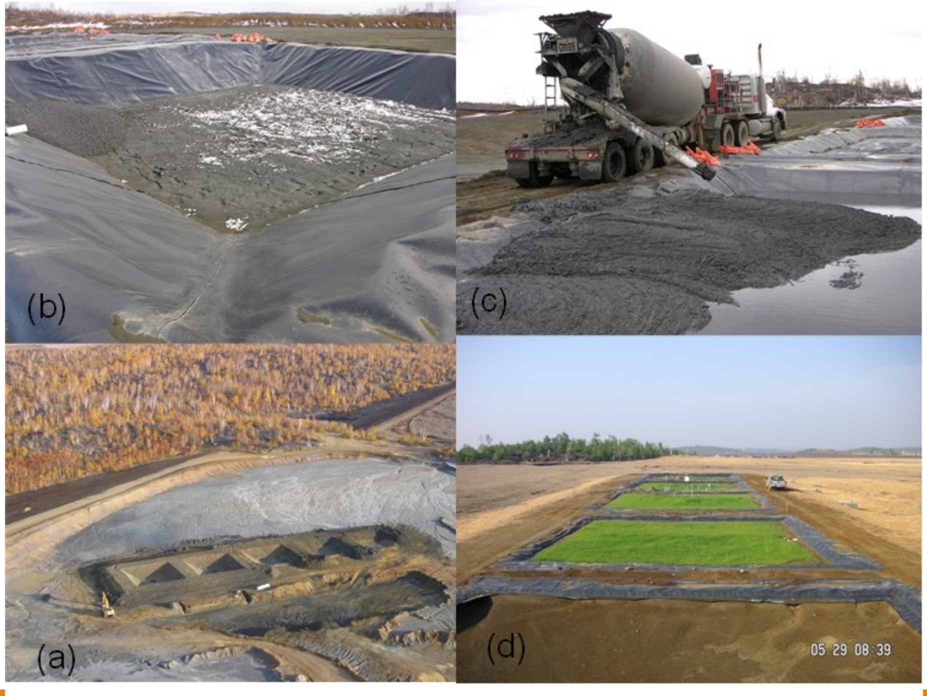
Tailings and Waste Rock

- Historically –tailings to TSF and rock to the WRD- managed separately because of vastly different physical properties- "never the two shall meet"
- For sulfidic material, maintaining saturation is the key to stopping oxidation – Subaqueous containment of tailings in a TSF (water cover) the solution if water balance is OK. So, Problem Solved?
- Recent collapses of major TSFs in Canada, Brazil and elsewhere have caused the concept of water covers on TSFs to be seriously challenged/revised on long term geotechnical stability grounds. Many companies are now moving away from slurry tailings disposal in above grade TSFs
  - – in pit disposal, dewatered tailings, dry stacking.
- Achieving geochemical stability in waste rock is a vastly greater problem than for tailings, but is combining the two an answer?

Tailings and Waste Rock – A Marriage Made in Heaven?

"Commingle" - "to combine thoroughly into a harmonious whole"- as distinct from just "blending"

1) Producing Geochemical and Physical Stability in Mine Waste Deposits-The Big Picture: Case Studies in Commingling Part 1 - Ward Wilson et al
2) Case Studies in Commingling Part 2: Water balance observation from field-scale commingled and waste rock test piles in a sub-tropical highland climate - Joseph Scalia et al
3) Potential Benefits of Comingling Waste Rock and Tailings as Indicated from a Multi-Year Trial (*in a dry climate*) - Devin Castendyk et al
4) Quantifying the Benefits (*by numerical modelling*) of Comingling Potentially Acid Generating Waste Rock and Tailings - Daniel Skruch et al



- *Field Case studies (up to 2y duration) and modelling show potential for commingling to substantially reduce rate of oxidation and improve the water quality of waste pile drainage*

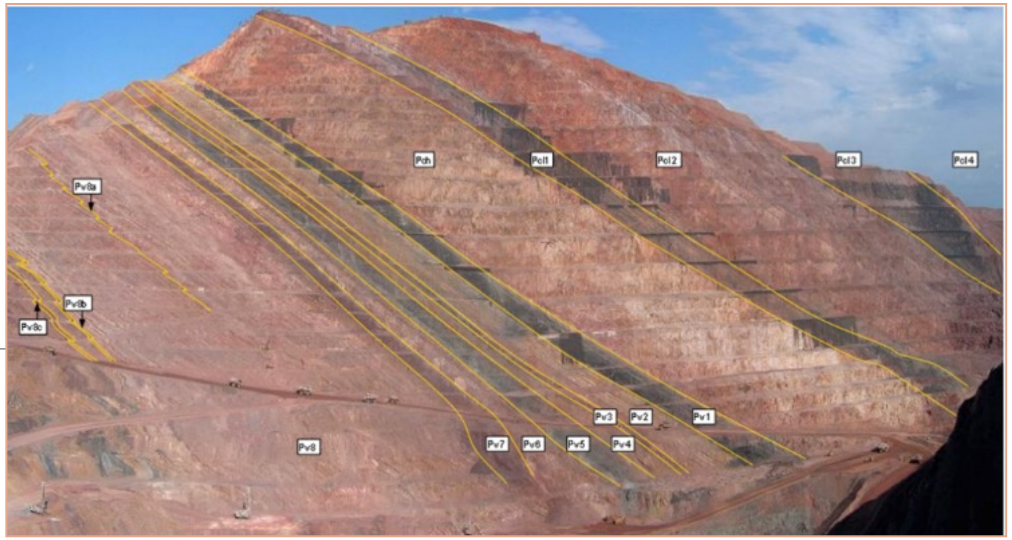
- *Can be used for cover systems and potentially applied to whole WRDs*

- *The optimum blend ratio is site specific - paste consistency required to achieve flow of tailings on mixing to ensure tailings will be retained in the voids of the waste rock*

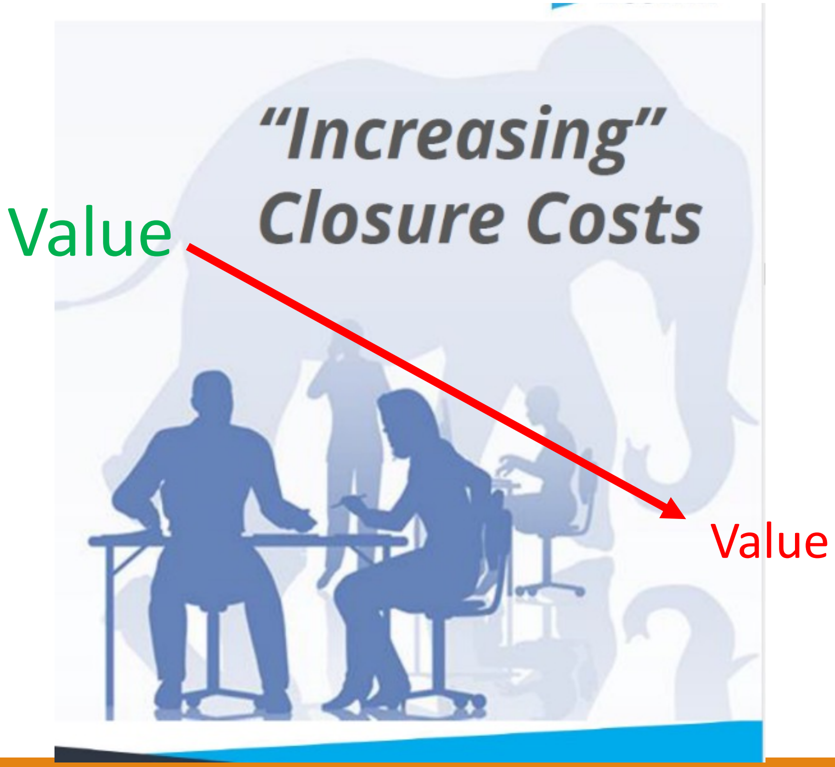
  - Ratio of rock to tailings may change over time

- *Challenges to Implementation*
  - *good mixing*
  - *equipment needed for full scale*

Mine Planning and ARD Waste Management



- ARD, Mining Economics and Risk: The Integrated View Driving Business Strategy - Neil Tyson - Deswik
- Value of proactive ARD management – Kim Ferguson BHP
- Integration of Waste Characterisation and Material Balance into Progressive Rehabilitation and Closure Plans - Greg Maddocks et al
- Say What You Mean and Mean What You Say: Determining the Period-of-Performance for Managing Reactive Sulfide-bearing Mine Wastes - Mark Logsdon



Mine Planning- The Risk of Progressive Failure in Controlling ARD

Complex Systems failure

Drifting into ARD (planning) failure is a gradual, incremental decline driven by:

- Geological / geochemical uncertainty
- Early decisions based on incomplete information embedding/propagating latent risks
- Incidents do not precede planning “failure”. Normal work does.

Red Flags

- Unrealistic constraints on allocated scope or time
- Normalization of risk e.g. through terminology use
- Stay in your lane’ - silos
- ‘The board had no way of knowing’

Technical Integration
Characterisation+Mine Plan+Waste Management Schedule

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Team Integration
across Operational Areas

Mine Planning and ARD

The 'value' lost from poor proactive management during operations

Case study = Selbaie, Eastern Quebec, 800km from Montreal; Tailings and mined rock have similar geochemical traits: ~90% potentially acid forming material, median sulphur content ~1.5%

Mining operations ceased 2001, closure via approved plan occurred ~2001 to 2005

Limit water and oxygen with a vegetated till cover over WRD –Was planned to be low permeability; **In reality till used for job was highly permeable silty-sand**

Current situation:

–Treating 2Mm^3 of contact water annually (CAD$10M/y for 800+ years)

But only have 250–300 years of sludge storage capacity in pit!

Closure cost increased to17% to 36% of estimated revenue from copper produced ...more coming....?

Mine Planning and ARD-Case Study-What IF?

Full value informed decision making

	No backfill mine plan	Progressive backfill mine plan
Cost	$369M	$335M
High Grade (kt)	87,574	87,354
Total non-ore material moved (kt)	231,672	228,691
Total PAF material above surface on closure (kt)	231,672	0
Closure risk	Higher – long term waste dump stability & rehabilitation OR cost of post-mining backfill, AMD management / clean up. Ongoing risk exposure	Lower - reduced costs for rehabilitation, revegetation, maintenance. Fewer erosion / stability risks, limited to no AMD impacts to rectify. Limited ongoing risk exposure
Closure uncertainty	Higher – stability, AMD control, pit lake quality, groundwater interactions	Lower – groundwater interactions with backfilled material
Long term impact on surface water	Surface water catchment permanently altered by pit and waste rock dump	Surface water catchment permanently altered only by pit

Cos
retrosp
backfill
- $32
clear

Characterisation – Static Methods

- Growing use of primary mineralogy to characterise and classify mine wastes. All existing static geochemical methods are designed to clarify the mineralogy of a sample and estimate net consequences of reaction (AP, NP).
  - Accurate and cost-effective mineralogical analysis techniques (eg. Quantitative X-Ray Diffraction, Hyperspectral Scans, Automated SEM methods, QEMSCAN techniques) for direct rather than inferred assessment of ARD characterisation and classification.
  - QXRD methods are now more accurate than before, utilise larger sample masses (more representative) than most chemical tests and are increasingly lower cost. One analysis can replace many static tests.

Characterisation - Mineralogy

1) Mineralogy from Quantitative X-Ray Diffraction (QXRD) for direct calculation of static geochemical properties - Soltys et al.
2) Mineralogy from both Quantitative X-Ray Diffraction (QXRD) and Hyperspectral Scans for direct calculation of static geochemical properties - Taylor et al.
3) Mineralogy from automated SEM methods to directly calculate sample geochemical properties - Bromstad et al.
4) Mineralogy from QEMSCAN methods to directly calculate sample geochemical properties - Ketchum et al.
5) Mineralogy from QEMSCAN methods to directly calculate sample geochemical properties - Wickham and Schofield.

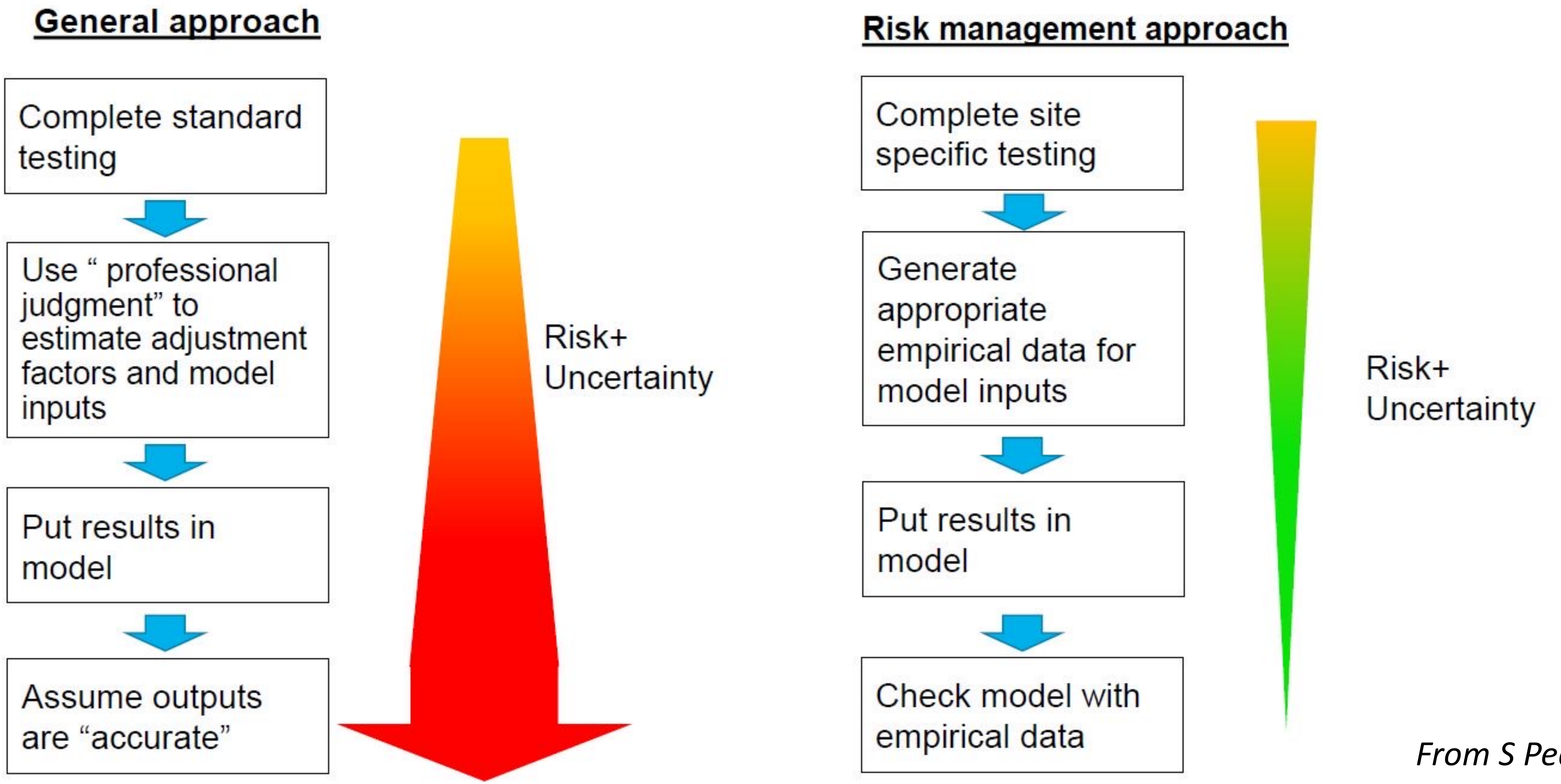
Characterisation - Kinetic Tests

A critical review of kinetic testing methods for mine waste geochemical assessment- S Pearce et al

- **Tests such as the (humidity cell test (HCT) are often used for the objectives of determining kinetic mineral weathering rates AND predicting drainage water quality. However, in trying to achieve both objectives the method is inherently flawed.**
  - L/S Ratio HCT 27:1; Field 0.01 to 0.1
  - HCT are not appropriate to estimate metal leaching when considering typical water quality from waste facilities
- **Addressing these objectives separately may be a better approach – HCT and oxygen consumption for kinetics, and leach columns (site specific conditions) for water quality**

- *If industry is serious about more robust risk management (refer to lessons from tailings dams) a new direction is required with respect to management of AMD risk through adoption of more appropriate context-relevant testing methods*

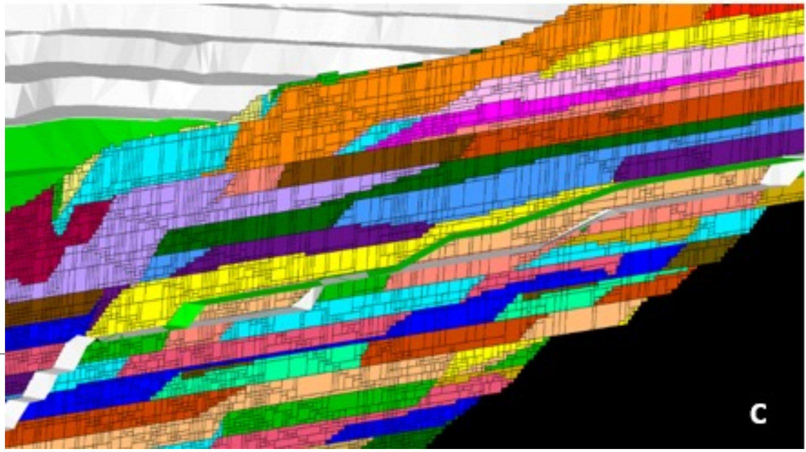
Characterisation Methods Contd



From S Pearce

Predicting Drainage Quality

Assessment of Drainage Quality from the Waste Rock Dumps at the Argyle Diamond Mine, Western Australia - Brown P & Rayner M –Rio Tinto



- *Block model developed using historic survey and placement records for the WRDs that overlay 5 drainage catchments, and coupled with a geochemical analysis to derive temporal water quality data for each drainage catchment.*
- *The mine is now closed, and the geochemical analysis was a key aspect in closure planning that enabled determination of whether the dump drainage might need to be managed post-closure.*
- ***Model indicated the aqueous flux of solutes would peak before placement of waste in the dumps ceased in 2012, and showed that the solute flux from the dumps will continue to decline as the material progressively oxidises.***
- *Regional aquatic ecological assessments showed that biota had only been subtly affected by drainage from the waste rock dumps prior to 2012, so post closure prognosis is good.*

Treatment

The evolving nature of active, passive and semi-passive mine water treatment technologies - Bob Kleinmann et al

- Addition of amendments to enhance/stimulate treatment processes has enabled the size of these systems and range of application to greatly expand from the original concept.
- Selection decisions are often based on the personal experience (or lack thereof) of the decision-making individuals rather than more quantifiable aspects, such as water chemistry and flow.

Microbes in Mining – Applications in Source Control and Mitigation of ARD - Lisa Kirk et al

- The Saturated Rock Fill (SRF) pit used by Teck Resources (Elkview in BC) from 2018 on to treat nitrate and selenate in mine water is likely the most successful industrial scale example of microbial source control and mitigation of water quality impacts in the mining industry today.

Revisiting Bactericides: a 40-Year-Old Technology to Suppress Acid Rock Drainage, James Gusek

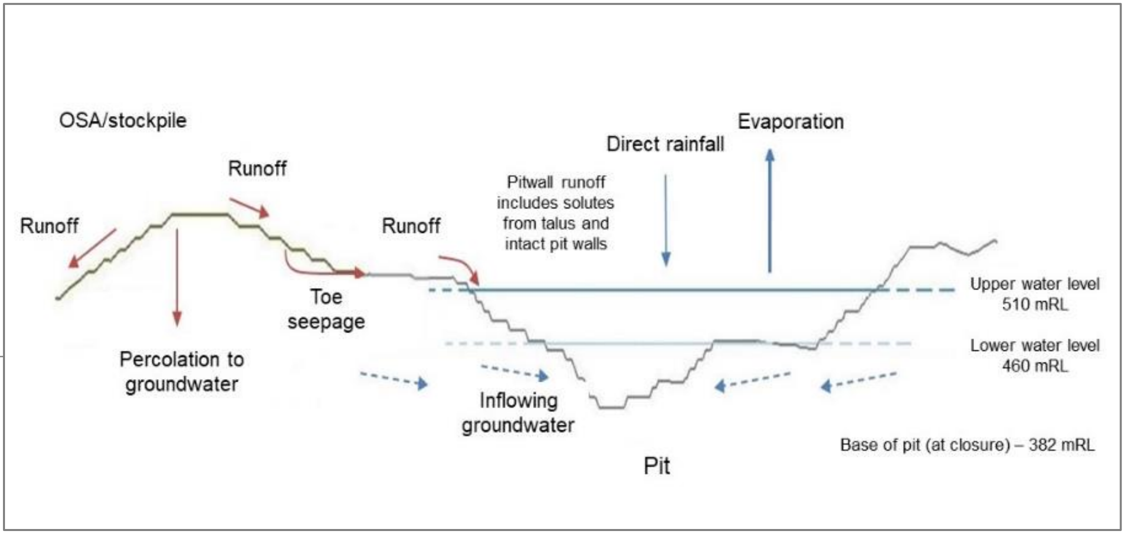
- Data from multiple sites shows that single campaigns of anionic surfactant-based bactericide application can last for several decades
- Revegetation appeared to be a key step in the long term success of the bacterial suppression process- organic acids generated by seasonal plant root degradation provide another antibacterial reagent that takes over from the initial applied man-made biocide such as SLS

Pit Lakes

- The Future Direction of Pit Lakes: Recommendations for Researchers, Industry Managers and Regulators - Devin Castendyk et al
- Pit lake water quality – a comparison of model prediction and field observation - Claire Linklater et al
- Strategies for Pit Lake Water Management and In-Pit Bioremediation– Martin et al

Pit Lakes Contd

A lot of predictive work of varying levels of sophistication is being done around the world on proposed pit lakes for closure



- **Relatively few well documented (monitored) longitudinal case studies (across climate regimes and commodity types) of pit lake performance in the public domain to be able to compare with original predictions**
  - this, combined with use of often proprietary in-house models is a barrier to improving predictive capability more generally and to gaining acceptance by regulators.
- **Never assume *a priori* that a pit lake will be/remain well mixed – chemical, thermal and wind drivers**
- **It has been assumed that pits in arid areas will be perpetual ground water sinks because of vast excess of evaporation over inputs. However, this is NOT necessarily the case (over decades to centuries)**
  - evaporation rates decrease with increased salinity and ultimately the dense saline water could flow outwards into the surrounding GW.

A Regulator’s Perspective

Best practice principles for mine waste cover systems and mineral mine rehabilitation in Queensland, Australia - Emma Gagen et al

- *Despite a wealth of published information about cover system design and the prevention of AMD from mine waste, convincing examples that demonstrate cover system performance and good rehabilitation outcomes from metal mines in Queensland are scarce.*
  - *On the contrary, there are numerous examples of AMD from covered and uncovered mine wastes, many of which are now abandoned sites, requiring remediation.*
- Cover systems effectiveness in Queensland, design details and construction costs have become a hotly debated topic in light of the recent legislative reforms in Queensland relating to financial assurance and closure plans.

So why should regulators “trust” mining companies in the absence of provision of robust and longer term performance monitoring data?

Emerging Topics

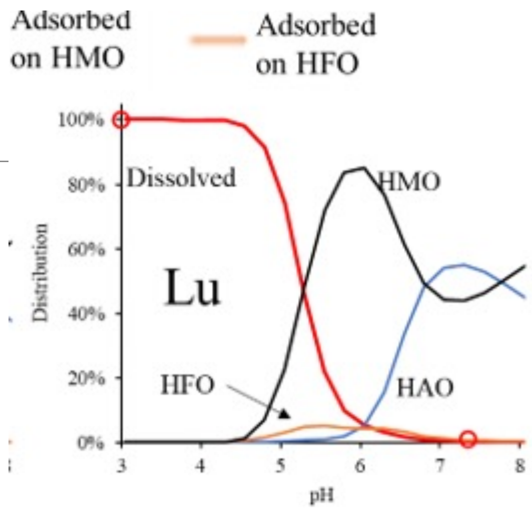
- Identifying potential contaminants of concern in lithium mine waste to limit environmental impacts Roslin Chen et al
  - -Demand for Li x5 over next two decades
- Recovery of Strategic Metals from waste streams
- Sulfide oxidation and carbonate neutralisation in mine wastes generates globally significant CO_2 emissions. Jeff Taylor et al

Lithium Mining

- The most abundant sources of ore-grade lithium are brines or LCT-type (Li-Cs-Ta) pegmatites. **Pegmatites currently represent around 60% of Li resources worldwide**.
- In Canada, there are 11 lithium mining projects at different stages of development – 3 (from Quebec) provisionally assessed for ML/ARD potential using geological characterisation reports available from the Canadian Impact Assessment Agency Registry website.
  - Combination of static, kinetic and leach tests
  - Kinetic tests (20-46 weeks) suggest that even if some lithologies were initially assessed as PAG based on the static test results, overall pH values are near circum- neutral
- Amphibolite, pegmatite, grabbo, basalt lithologies and tailings are potential sources of leachable As, Co, Ni and Cu so ML could be an issue – potentially requiring waste segregation and containment to manage.
- **Currently insufficient aquatic toxicity data to establish a robust chronic exposure surface water quality guideline value for lithium.**

Recovery of Strategic Metals?

- Water-Quality Modeling Tools to Evaluate Acid Mine Drainage Treatment Strategies for Recovery of Rare-Earth Elements - Charles Cravotta
- Determination and Prediction of Rare Earth Element Geochemical Associations in Acid Mine Drainage Treatment Wastes - Benjamin Hedin
- AMD Processes, Wolframite Stability and Chemical Forms of W in W-Mo Tailings: A case Study from Queensland Australia – Zhengdong Han et al



CO_2 Emissions

Acid generating iron sulfides (eg. pyrite) are present with the majority of mineral commodities (and mines) worldwide

- Carbonate minerals are often associated with all of these deposit types
  - Not all of the carbonate minerals are acid neutralising, but all release CO_2 upon reaction with acid
- O_2 consumption and CO_2 production rates have been examined as a function of material type, sulfide content, sulfide type, carbonate content, particle size, moisture content and oxygen concentration.
- Modelled - Acidity Generation and Carbon Dioxide release by Domain and Mine Scale and by Commodity Type.
- **Estimated that 30-270 million tonnes of CO_2 is released from accumulated sulfidic mine wastes globally per year (ie. 0.1-0.7 % of total global anthropogenic emissions of 40 billion tonnes per year.**

Does not include CO_2 emissions from the lime used in ARD mine water treatment plants (need for a global inventory of lime consumption by the mining industry). This is an horizon issue for "Treatment in Perpetuity"

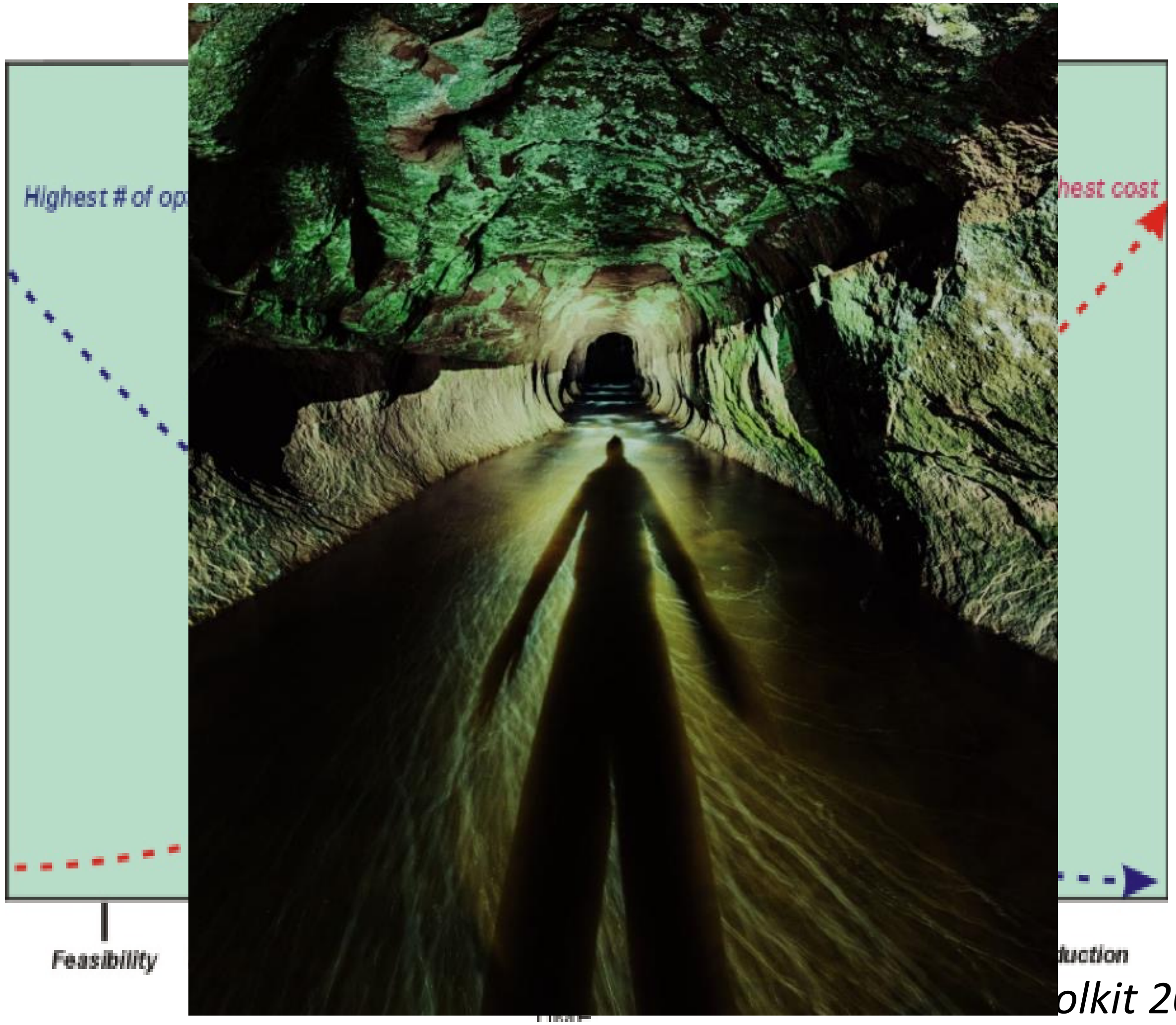
Take Home Message (1)

- *Need to have the right knowledge at the right time!*
- *When there is adequate <u>technical assessment</u> <u>and time</u> to evaluate a range of viable operational and closure options, the opportunity for better overall outcomes increases.*
- *The characteristics and quantities of AMD materials exposed by mining can change significantly throughout the LOM, and sites often fail to capture, review, and evaluate these changes and update the AMD management plan.*
- *<u>Value in modelling and value in experimentation</u>*
  - “All models are wrong, get over it" -trials required
- *BUT (field) trials take several years to yield robust results, so need to get started early.*
- *<u>Good Monitoring</u> –real life results to prove performance to regulators and communities.*

Take Home Message (2)

Proactive Measures for Lasting Outcomes
or
"A Stitch in Time saves Nine"

"Source Control – the gift that keeps on giving!"



olkit 2004

A recent project identified the difference between operational fleet movement vs a third-party closure contractor = 4x

Cost of remediation at closure can be 5x cost of prevention


Questions?