Mineral Waste Management Considerations in integrated closure planning

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Overview

1 The problem – sulfidic / reactive mineral waste

- Coal mines
- Hard rock mines
- Reactions and implications

2 Management

- Characterisation – understand your issues
- Management strategies
- Planning for closure through landform design
- Integration with mine scheduling

3 Monitoring / validation for continual improvement

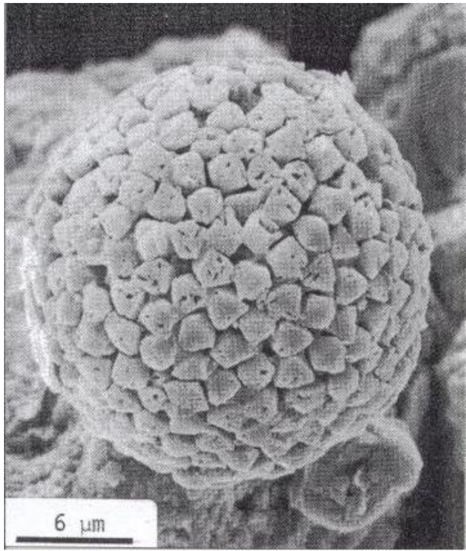
1. The problem – sulfidic / reactive mineral waste - overview

- The key problem is chemically reactive mineral wastes containing sulfides.
- The main culprit in usually pyrite (FeS_2)
- Other sulfides may include:
  - Arsenopyrite (FeAsS)
  - Chalcopyrite ($CuFeS_2$), covellite (CuS), bornite (Cu_5FeS_4), chalcocite (Cu_2S)
  - Sphalerite (ZnS)
  - Galena (PbS)
  - Pyrrhotite (Fe_6S_7 – $Fe_{11}S_{12}$)
  - Pentlandite ($(Fe, Ni)_9S_8$)

- All react with oxygen in the atmosphere and water once mined resulting in various combinations of acid, metalliferous and or saline drainage risk (i.e. AMD, or acid and metalliferous drainage)

1. The problem – sulfidic / reactive mineral waste – coal mines

- FeS_2 in coal mines is generally present as framboidal pyrite – morphology is a function of the formative environment (sedimentary in this instance)
- Pyrite oxidation is a surface controlled reaction so that the larger the surface area (i.e. the smaller the grain size) – the faster the reaction kinetics
- The Bowen Basin contains largely terrestrially derived coals with relatively low sulfur contents of nominally up to ˜ 1 percent sulfur
- The northern Bowen around Collinsville contains marine derived coals with higher sulfur concentrations up to nominally 6-7 percent sulfur = bigger risk
- You need to understand your rocks and mineral waste in order to manage your risk



GHD

1. The problem – sulfidic / reactive mineral waste – hard rock mines

- FeS_2 in hard rock mines is generally present in cubic or octahedral forms – also based on the formative environment (igneous and/or metamorphic in this instance)

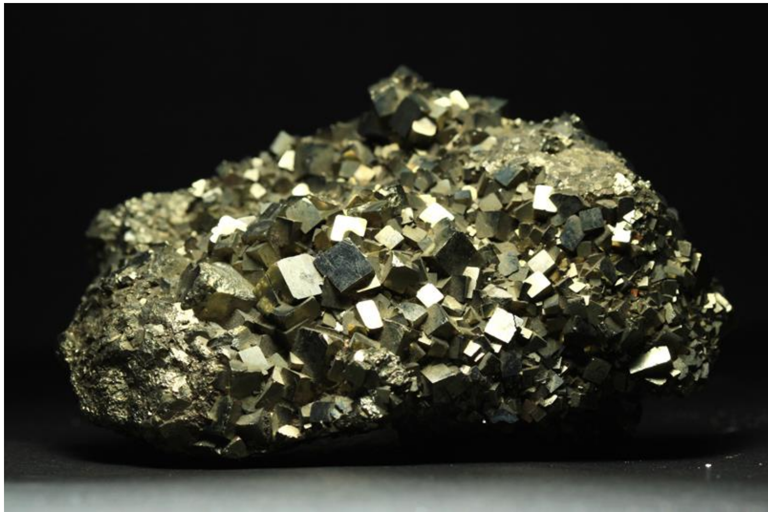
- Sulfide minerals are more common given the nature of the deposit; can be lead, zinc, copper, nickel, arsenic etc – these are in fact, the ore!

- The issue becomes managing low grade or in transitional zones where processing may not be cost effective and/or waste with sulfides present – gossans generally OK

- Pyrite commonly associated with quartz, and therefore, gold mines

- The best solution is to leave it in the ground!

  this is usually not an option though – so we need to know the enemy so we can manage it



1. Chem 101 – sorry!

- An overall summary reaction for pyrite oxidation by oxygen is:

$$FeS_2 + 3.75O_2 + 3.5H_2O \rightarrow 2SO_4^{2-} + Fe(OH)_3 + 4H^+$$

(pyrite) + (oxygen) + (water) → (sulfate) + (ferrihydrite) + (protons)

- If and when solution pH values get below around 3.5 (i.e. ferric iron solubility):

$$FeS_2 + 14Fe^{3+} + 8H_20 \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

(pyrite) + (ferric iron) + (water) → (ferrous iron) + (sulphate) + (protons)

- So once things get going, they self perpetuate and are very, very difficult to stop.

  E.g. The Rio Tinto in Spain (literally, the red river) – so named due to the dissolved iron as a result of acid and metalliferous drainage, First mined by the Iberians in around 3,000 BC and still contaminated……

1. Chem 202 – other sulfides

- Other sulfides, when present, can add to the problem:

$$CuFeS_2 + 16Fe^{3+} + 8H_2O \rightarrow Cu^{2+} + 17Fe^{2+} + 2SO_4^{2-} + 16H^+$$

(chalcopyrite) + (ferric ions) + (water) → (copper ions) + (ferrous ions) + (sulphate) + (hydrogen ions).

$$FeAsS + 13Fe^{3+} + 8H_2O \rightarrow 14Fe^{2+} + HASO_4^{2-} + SO_4^{2-} + 15H^+$$

(arsenopyrite) + (ferric ions) + (water) → (ferrous iron) + (arsenate) + (sulphate) + (hydrogen ions)

$$ZnS + 8Fe^{3+} + 4H_2O \rightarrow SO_4^{2-} + Zn^{2+} + 8Fe^{2+} + 8H^+$$

(sphalerite) + (ferric iron ions) + (water) → (sulphate) + (zinc ions) + (ferrous iron ions) + (hydrogen ions)

1. Chem 303 – last one.

- Latent acidity can also be an issue due to dissolved metals (iron, manganese, aluminium etc) precipitating downstream as pH values increase:

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$$

(ferric iron – or other) + (water) → (ferric hydroxide) + (hydrogen ions)

- But there are also neutralising reactions that can be natural or engineered:

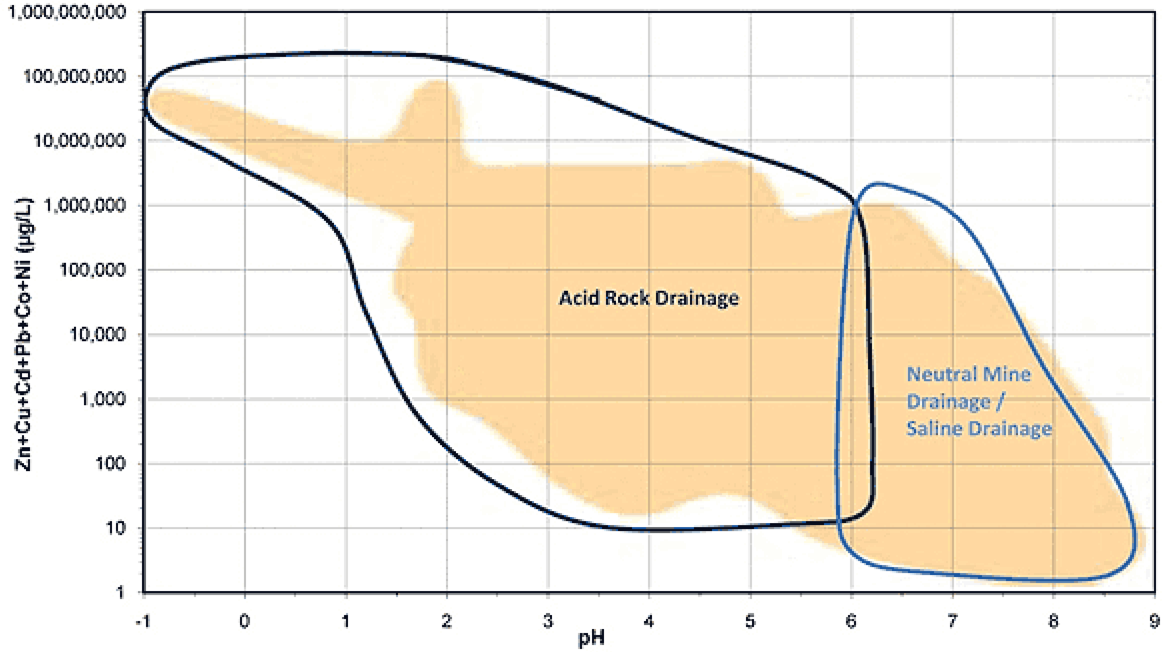
$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2O + CO_2$$

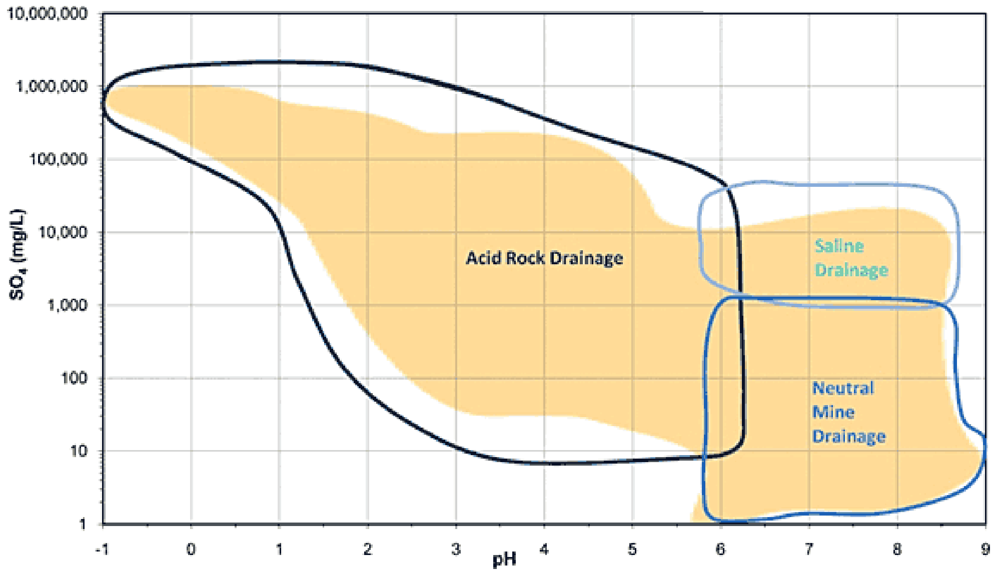
(sulphuric acid) + (calcite) → (gypsum) + (water) + (carbon dioxide)

- The latter reaction forms the basis of many management tools available.

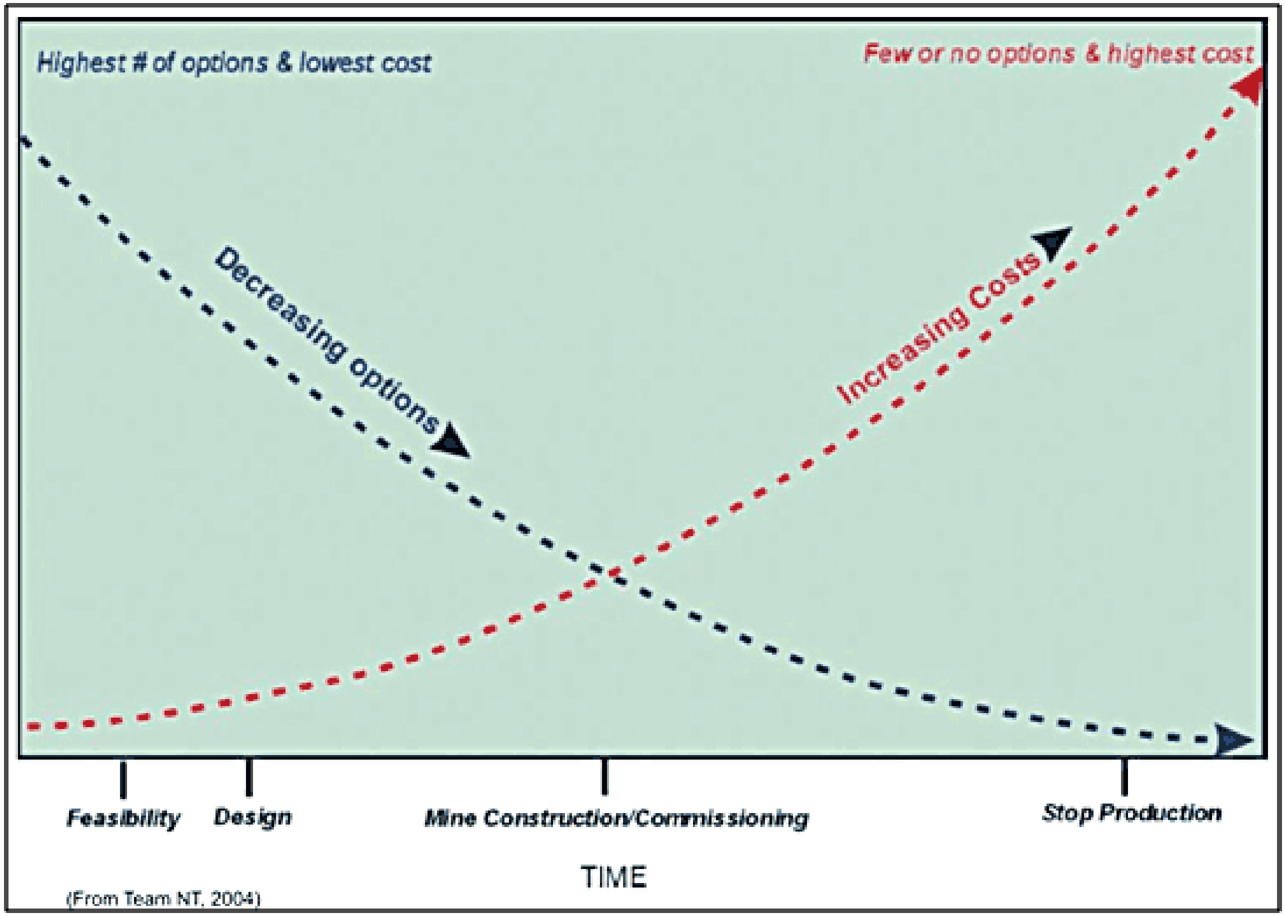
1. The problem – sulfidic / reactive mineral waste - overview

- From INAP (2009)





2. Characterisation – early knowledge = better results and less cost



2. Management – Closure Planning Framework

Closure planning activities are required throughout the lifecycle to enable an optimal closure plan to be implemented.

Approval → Operations → Transition (5-10yrs out) → Closure

Approval

- Scenario Assessment
- Impacts
- Mitigation Measures

↓

Mine Closure Plan (conceptual)

Operations

Operational Monitoring and Data Collection

↓

Mine / Closure Plan Changes? Compliance To Plan?

↓

Review Impacts Mitigation Measures

↓

Update / revise Closure Plan

Transition (5-10yrs out)

Detailed Executable Closure Plan

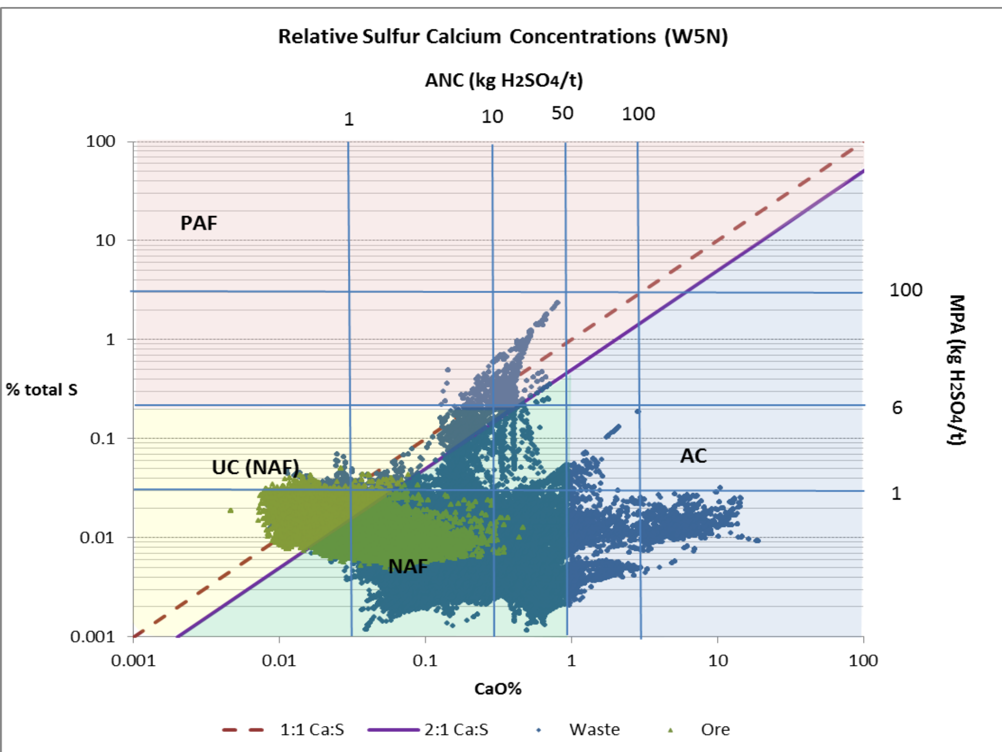
Closure

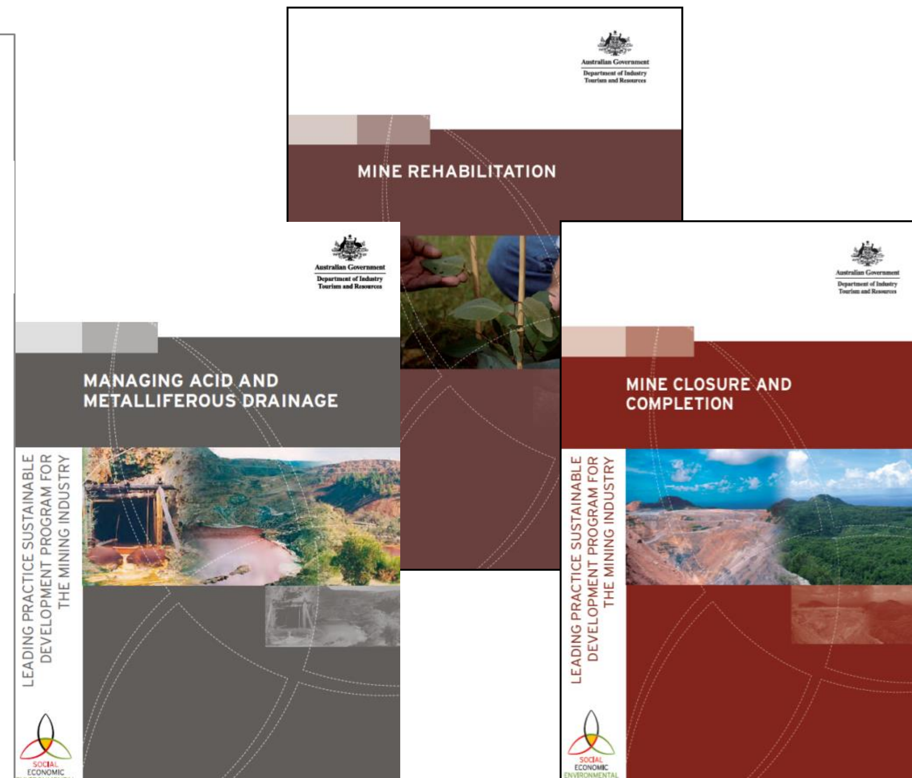
Closure Implementation

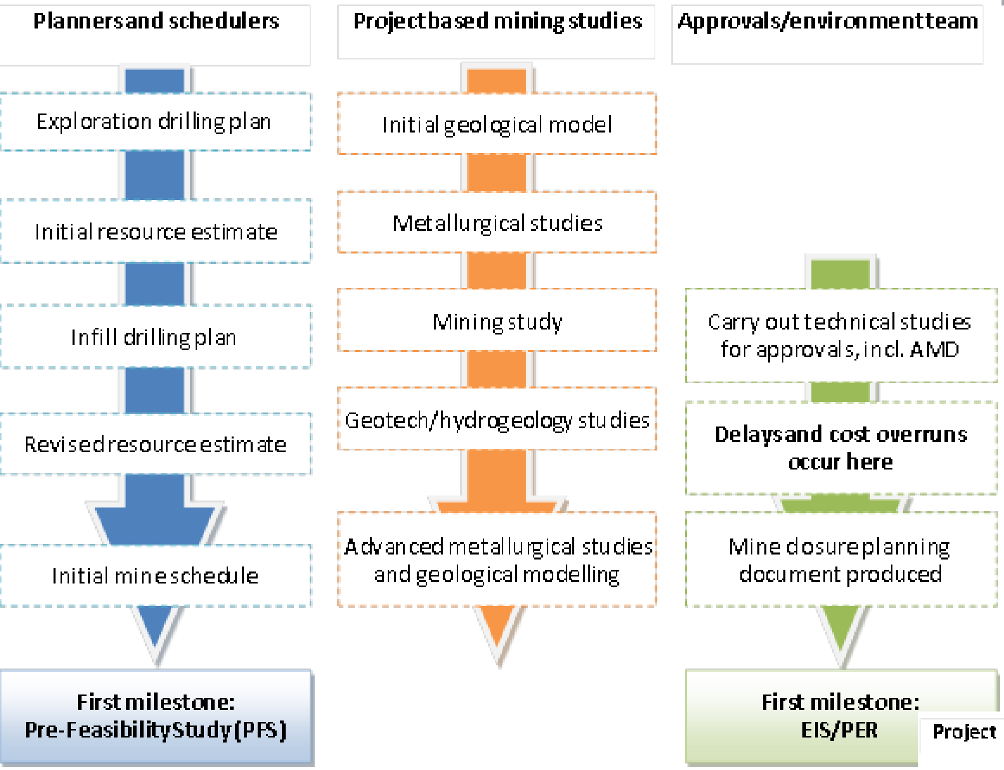
Incorporate mine closure and financial provisioning into annual life-of-asset planning.
Undertake routine 'closure scenario planning'
Ensuring new technical info considered

2. Characterisation

- Various stages from exploration through to operations.
- Refer to INAP (2009) http://www.inap.com.au/GARDGuide.htm and/or DITR (2007) etc
- Exploration can be as simple as analysing for S and Ca along with target species (% S can be used to determine maximum acid potential with Ca used to estimate neutralising potential – with some assumptions) – XRF can be useful.



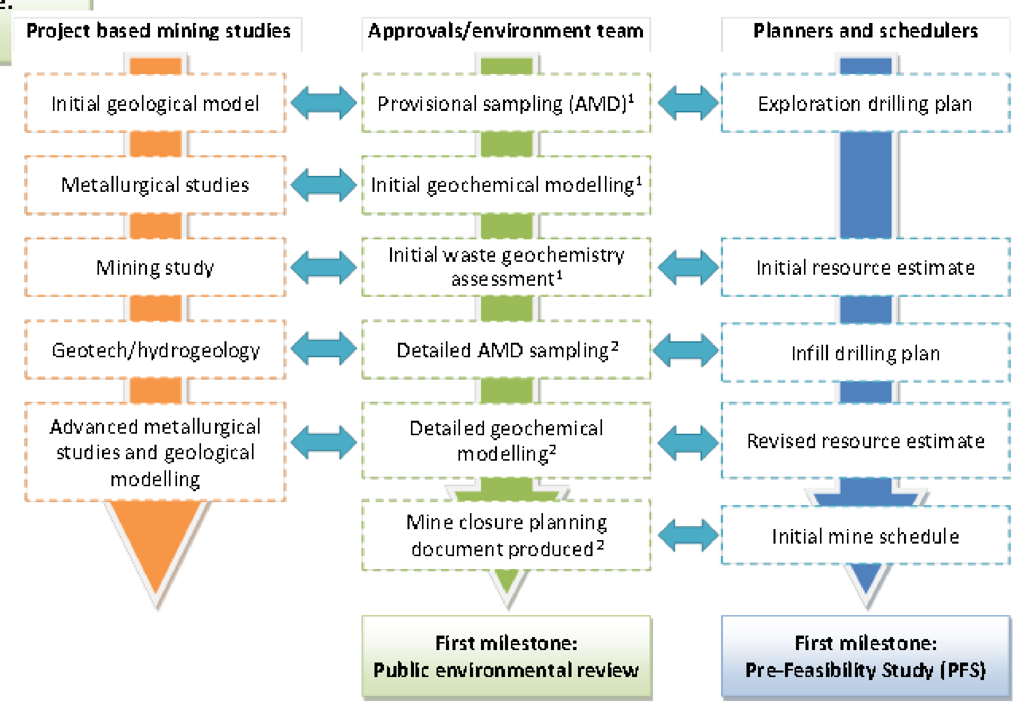




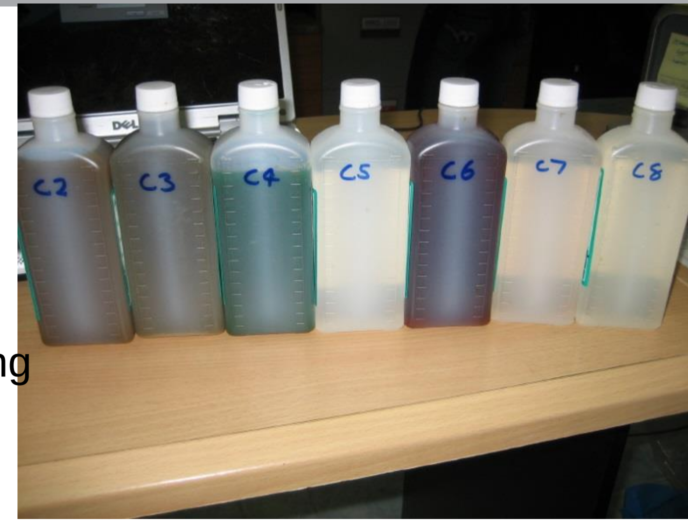
- <u>Integrated Teams</u>

BAD

GOOD



2. Characterisation (con'd)

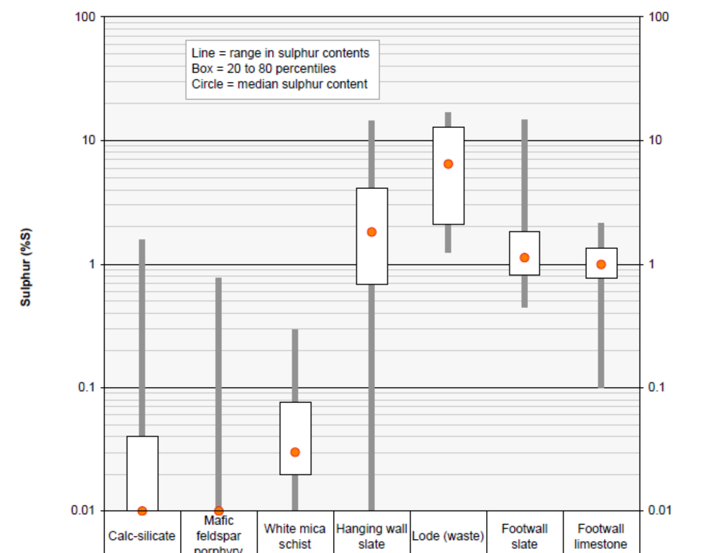


- Resource definition drilling stage / EIS should be more detailed to meet regulatory requirements; often including a conceptual closure plan

- Tests should include NAPP (ANC, net reactive sulfur – can be S_{Cr}, total S, SO_4 S), NAG – kinetic (pH and °C) or sequential NAG as required, Acid Buffering Characteristics Curves (ABCC), metals, TCLP/ASLP i.e. metals leaching, potentially kinetic columns/oxygen consumption testing.

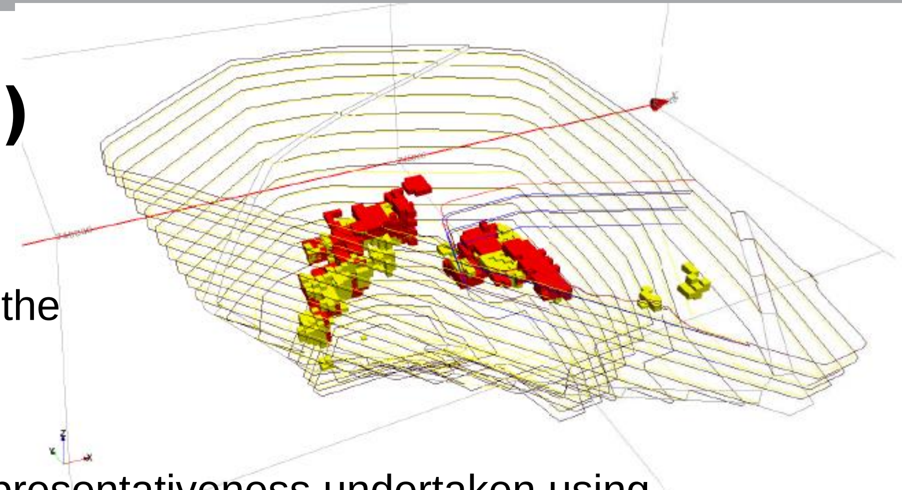
- All to identify your risk by target lithology that will be disturbed on site.

- The results then inform management options, materials handling and AMD/closure strategy = closure planning.

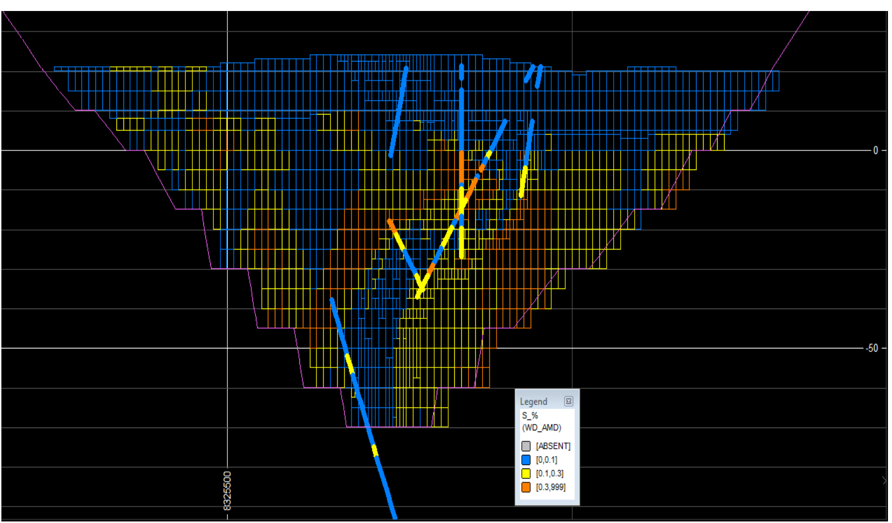


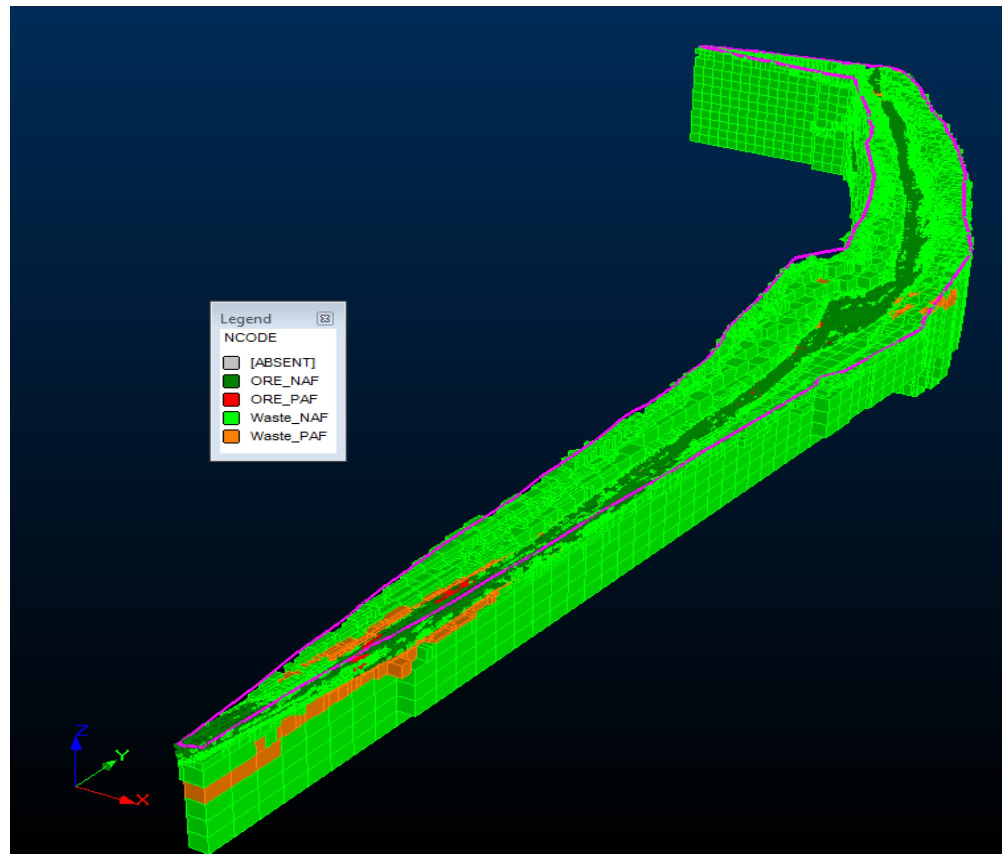
	Calc-silicate	Mafic feldspar porphyry	White mica schist	Hanging wall slate	Lode (waste)	Footwall slate	Footwall limestone
80 percentile	0.04	0.01	0.08	4.13	12.92	1.84	1.34
maximum	1.57	0.77	0.29	14.4	16.6	14.6	2.12
minimum	0.01	0.01	0.01	0.01	1.24	0.45	0.1
20 percentile	0.01	0.01	0.02	0.69	2.10	0.82	0.77
median	0.01	0.01	0.03	1.82	6.44	1.12	0.99

2. Characterisation (con'd)

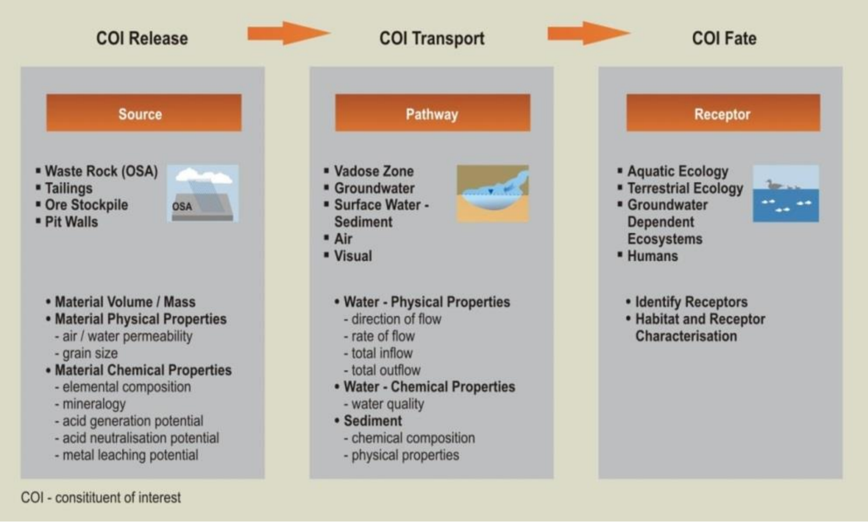


- Compile 3D geochemical model that talks to the resource block model (Vulcan, Surpac etc)
- Statistics including variography for spatial representativeness undertaken using software (e.g. Isatis)
  – regulators increasingly seeing waste characterisation as quasi-analogous to resource definition (JORC)





2. Management strategies (con’d)



- Your characterisation will inform your risk (see right)….. you may have no problem; i.e. physical stability considerations only.

- If you have sulfidic material that requires management, your strategies are largely based on pyrite oxidation science, being:

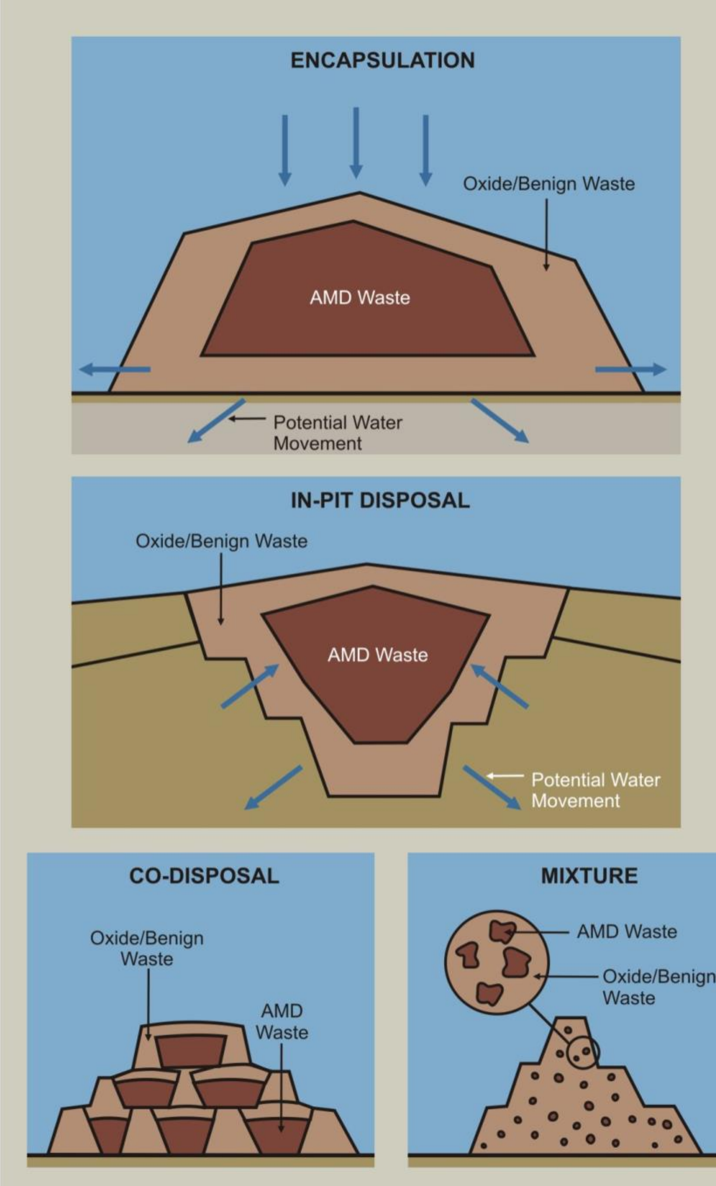
  1. Reducing the opportunity for pyrite to oxidise in the first instance
  2. Maintaining circum-neutral pH values so that iron oxidising bacteria aren’t happy + ferric iron solubility is minimised
  3. Reducing or eliminating the supply of ferric iron to the FeS_2 surface.

- The latter two are often too late (i.e. water treatment) while the former is preferable as it is more pro-active……there are several often used solutions in this regard.

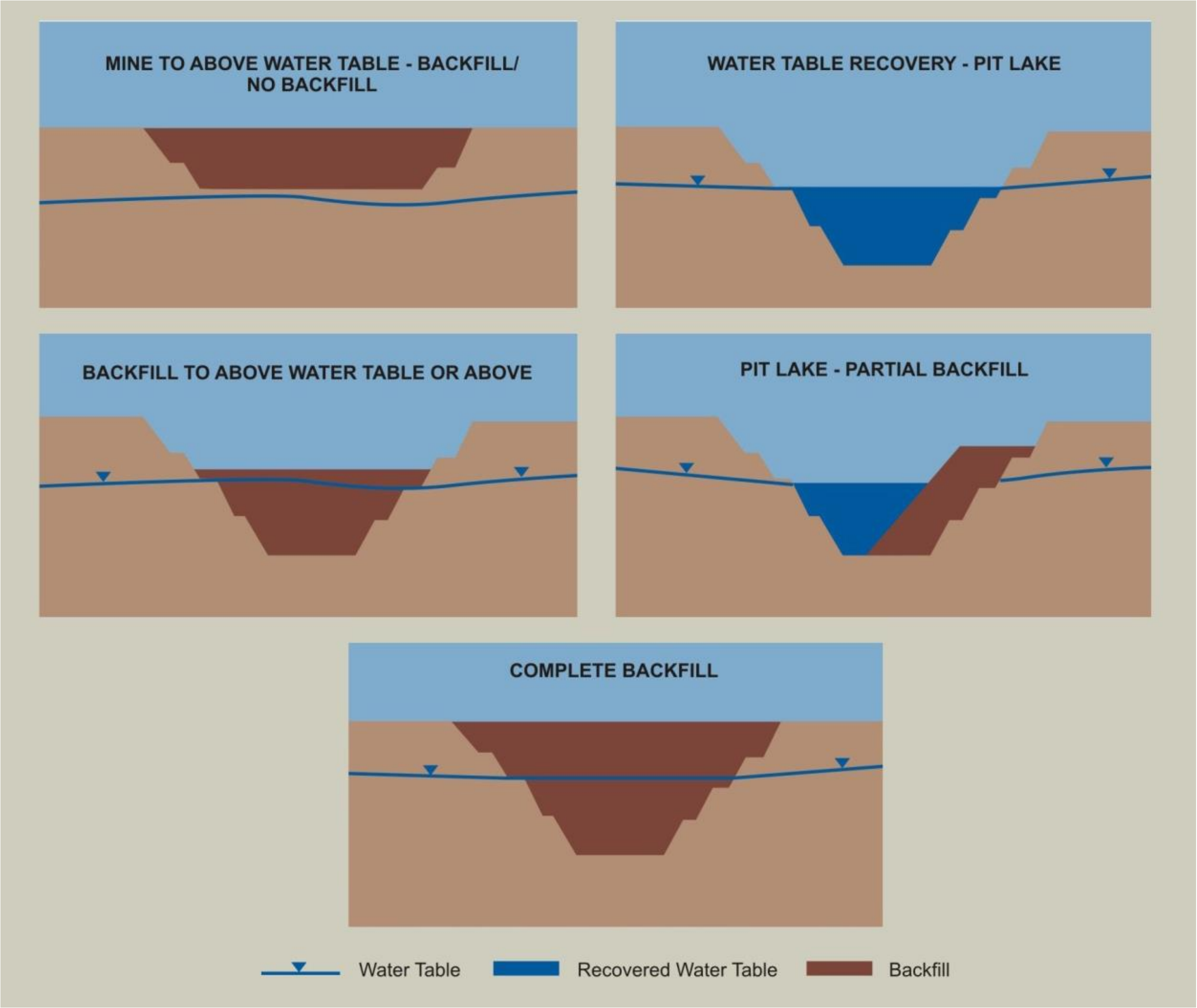
- All into the strategy and the Closure Plan……..

2. Management strategies (con'd)

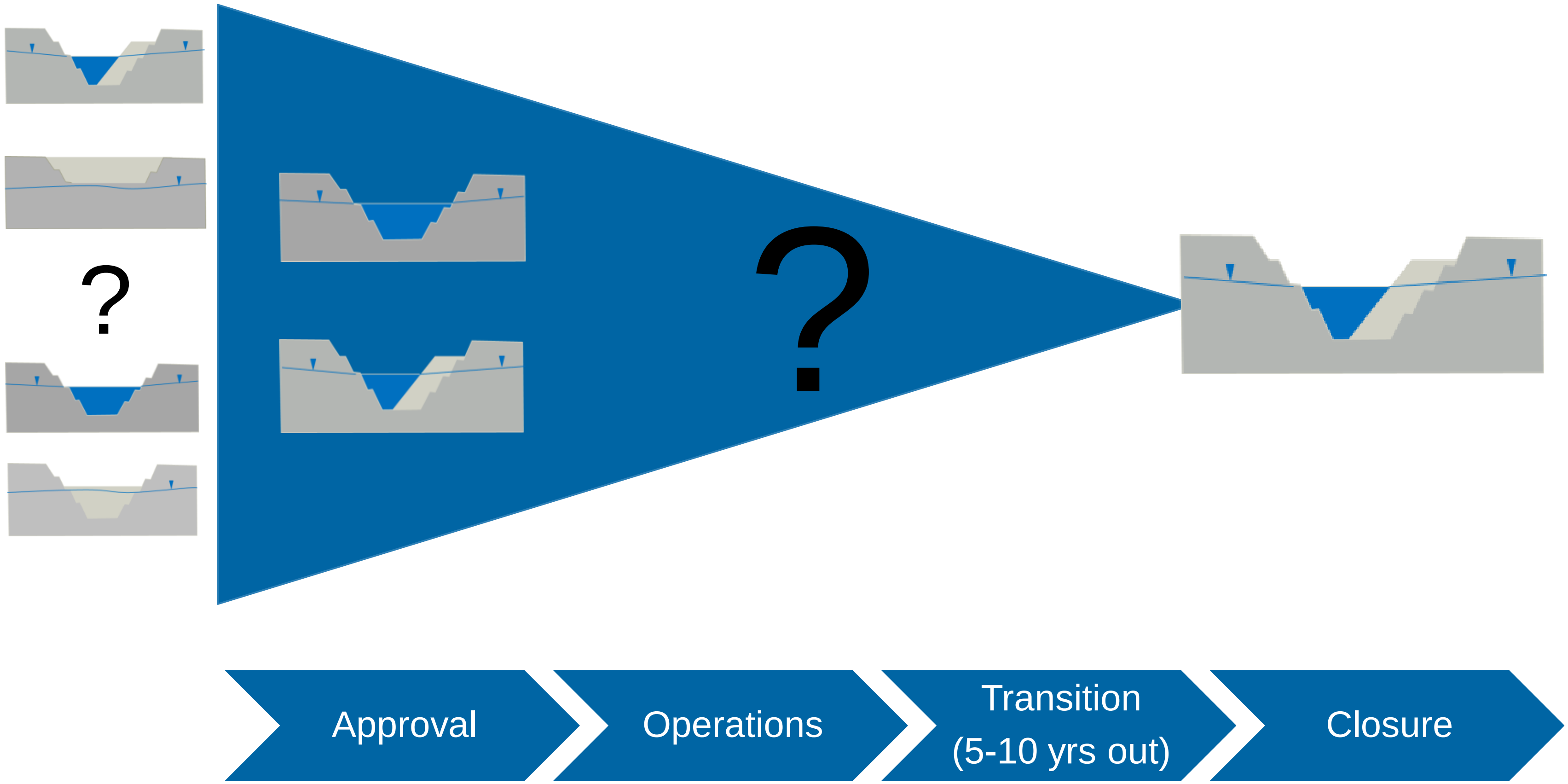
- If you have an issue with reactive mineral waste, a common approach to management is reducing FeS_2 oxidation – which generally means:
  - Desulphurisation (often not cost effective)
  - In pit disposal (multi-pit operations ideal) – can also be subaqueous disposal (e.g. Canada, Tasmania, Phu Kham – Lao PDR)
  - Ex pit disposal in waste rock dumps (most common practice?)
- In and ex pit disposal can also include mixing/blending co-disposal, and/or encapsulation (see right – DITR '07)
- No two sites the same – understand your risks



2. Management strategies – in pit….which option?



2. Decision Points – Life-of-mine planning

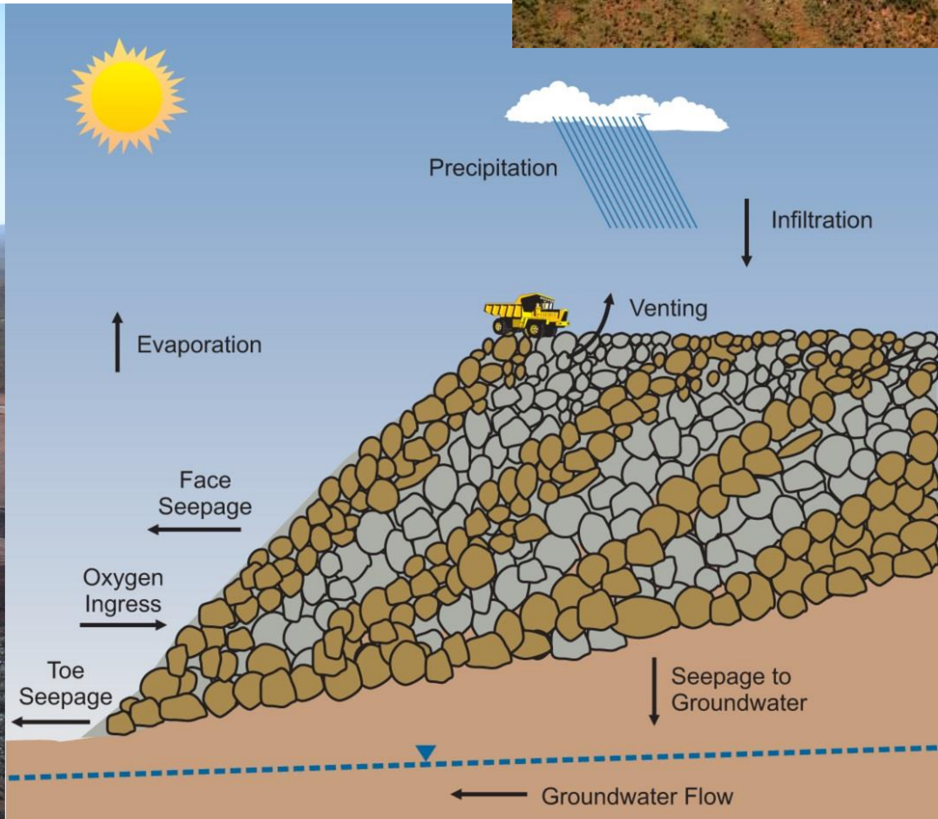


2. Management strategies (con’d) – Phu Kham
(cf. Miller 2014)

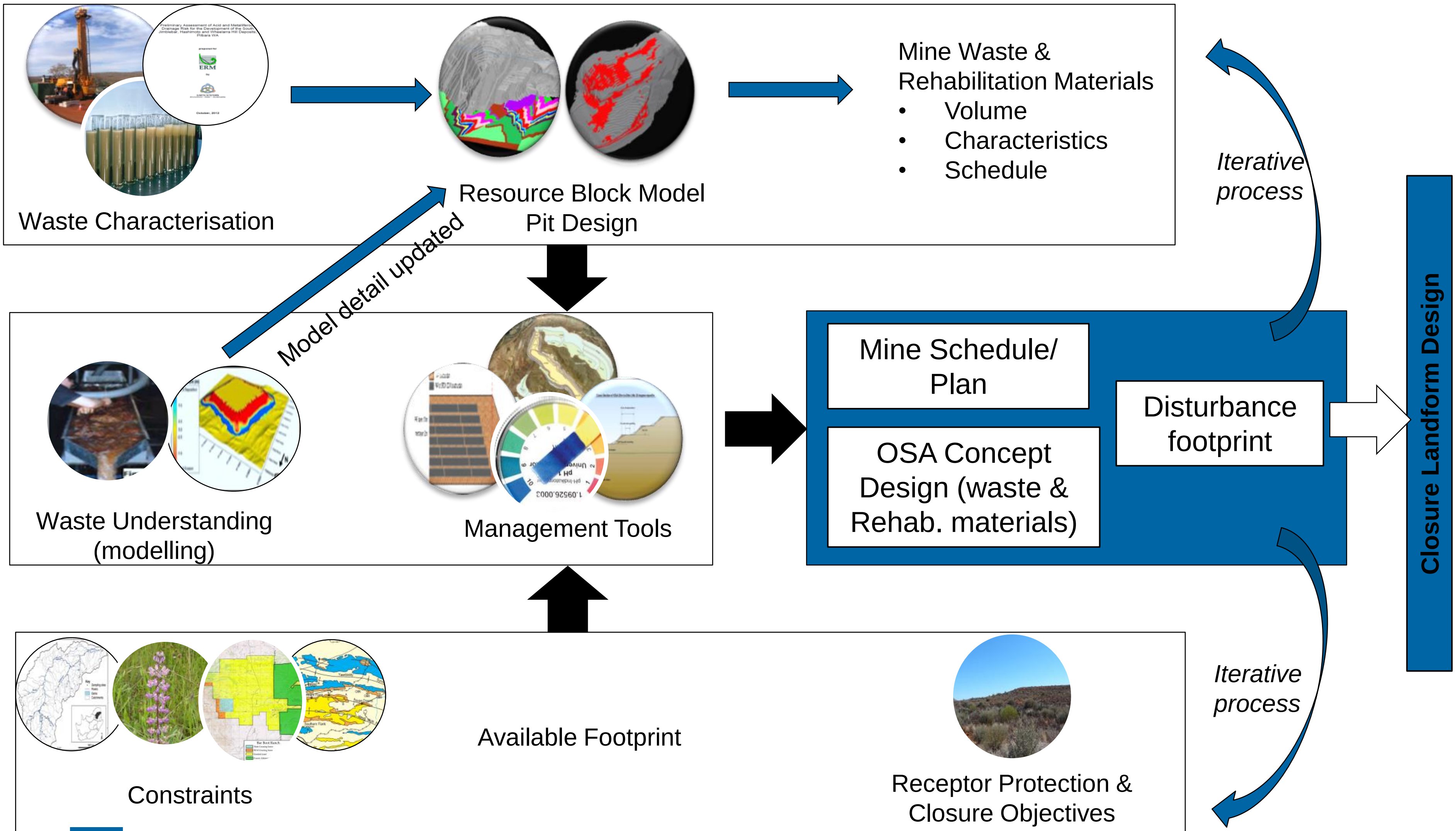
Fig. 6. **Waste Rock Management for ARD Control at the Phu Kham Mine in PDR Lao**

2. Management strategies (ex pit)

- Other considerations include landform design and materials placement and the implications thereof
- Multi-disciplinary team required (geos, mine engineers, schedulers, enviros, geochem, ecology, hydrology, hydrogeologists etc)



Closure Landform Design Process



2. Management - Receptor impact (AMD)

AMD – Acid & Metalliferous Drainage includes

Acid, sulfate and/or metals release in low pH or neutral pH drainage waters from mining processes

Poorly Managed AMD waste material

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Oxygenation = acid generating reaction initiated

↓

Pollution (acid, salts and/or metals)
(Overland/Surface water/Groundwater)

↓

Operations

↓

Threat to licence to operate
Remediation costs

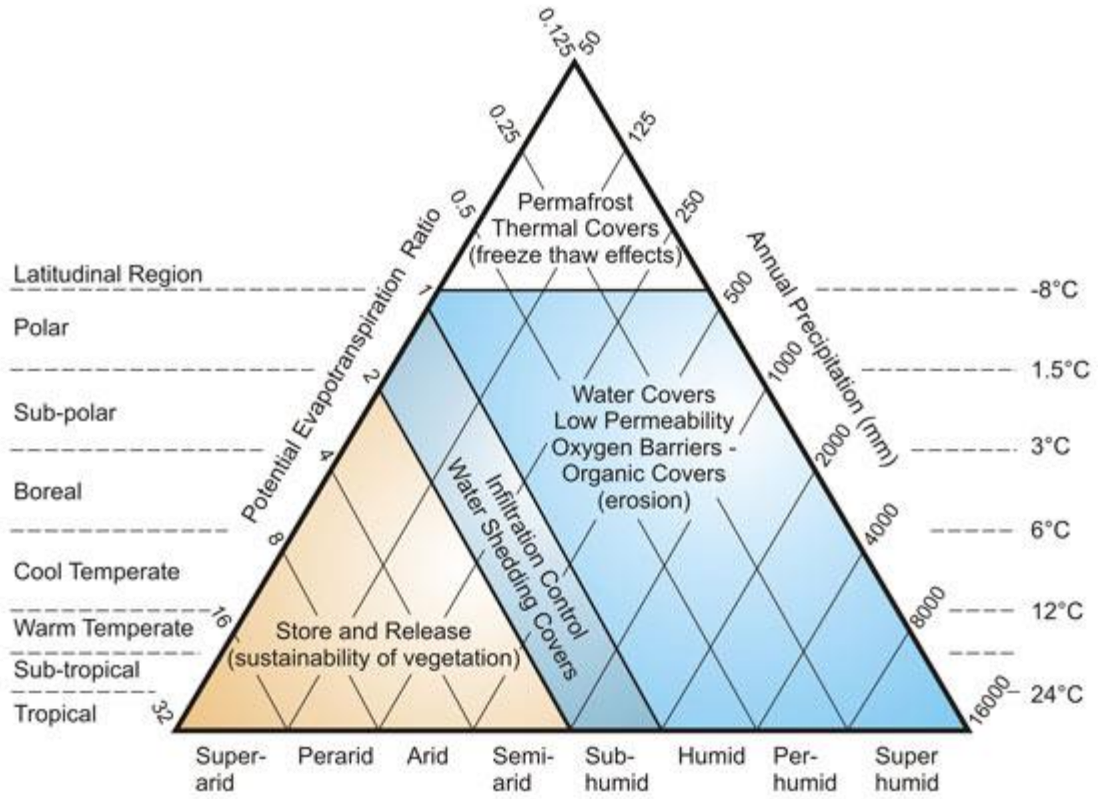
Closure

↓

Inability to rehabilitate
Failure to achieve completion criteria
Unable to relinquish
Remediation cost

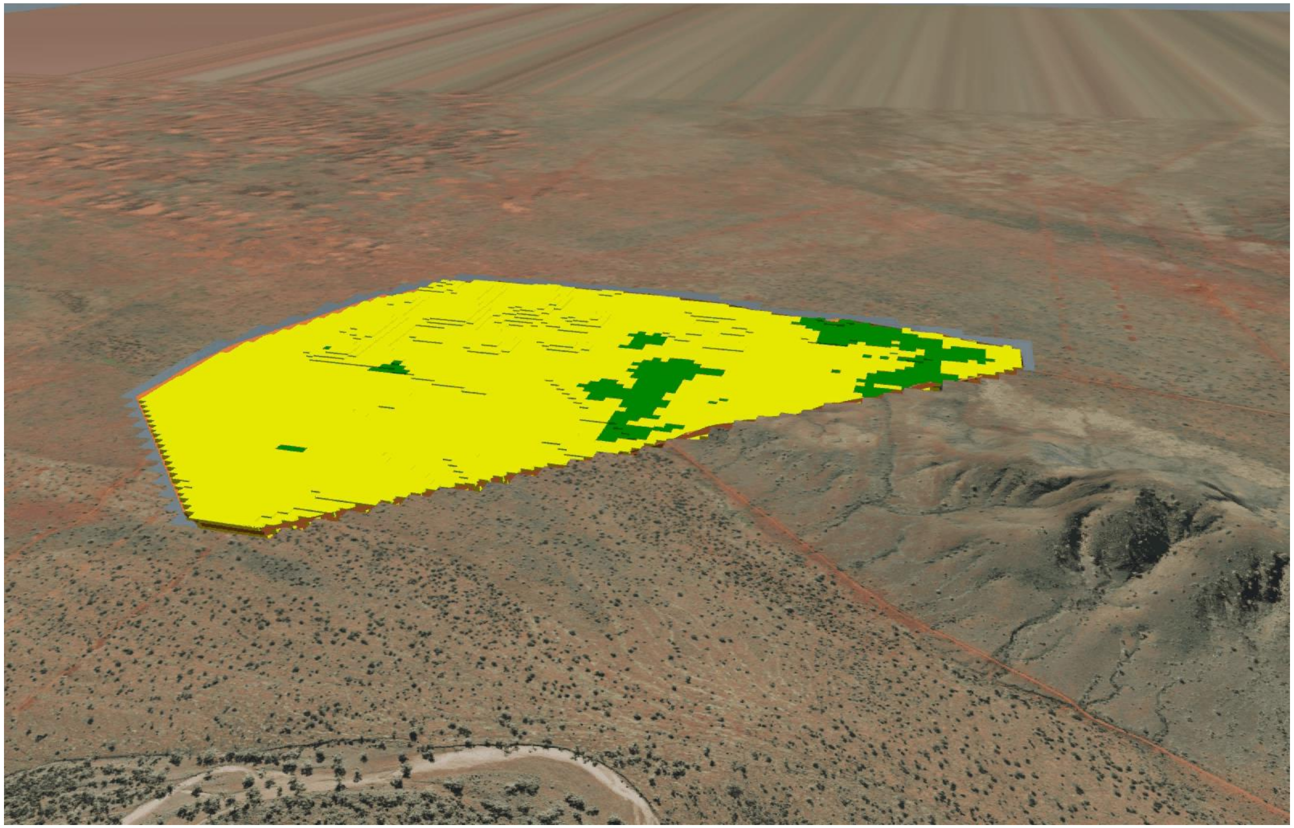
2. Management strategies – landform design

- Cover design also critical to long term physical and chemical stability



2. Management application - operations

- Integrate results of characterisation into the block model and then into mine waste scheduling / planning, and placement (i.e. ‘mining for closure’)



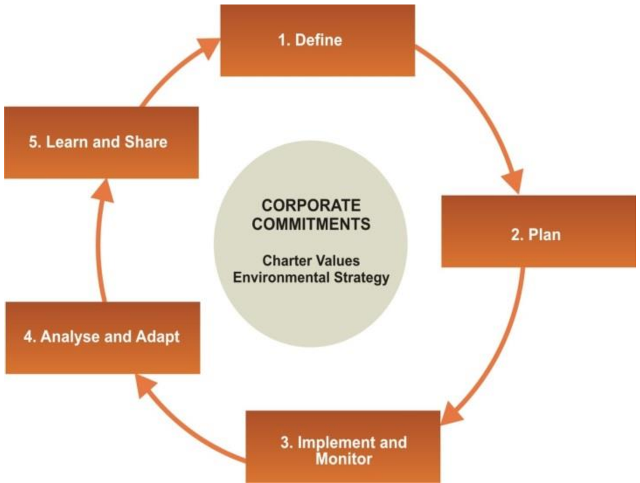
(cf. Pearce 2014).

3. Monitoring and validation

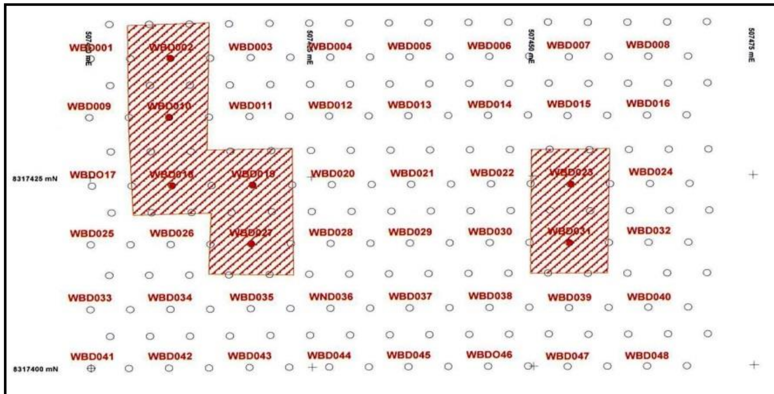
- Develop appropriate management and monitoring plans and procedures to ensure risk is monitored with management tweaks realised as required

- Validation / assurance sampling generally a combination of:
  - Visual inspection of landforms and drill chips for pyrite etc
  - Semi quantitative (XRF useful in advance blast holes / mining blocks)
  - Quantitative using NATA accredited laboratory (both mineral waste, SW and GW) – ensure the program 'talks' to the Water Monitoring Plan
  - Increasing use of temperature and oxygen probes in PAF cells / WRDs

- Plan / do / learn – 'adaptive management'



PAF waste zone interpretation from site sampling



3. Summary

- Take home messages:
  - ✓ Closure planning starts at exploration! – sort of. You may be surprised how much data you have laying around that can be useful.
  - ✓ Understand your risk – characterisation counts – it will save you $$ down the track.
  - ✓ Plan your closure strategy incorporating AMD management as required based on your risk.
  - ✓ Implement the strategy.
  - ✓ Monitor the implementation – adaptive management.
  - ✓ Progressive closure, rehabilitation and relinquishment = happy regulator and happy operator.

Thank you – Any questions?

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