ACID ROCK DRAINAGE (ARD)

UNIVERSITY OF ALBERTA

"uplifting the whole people"

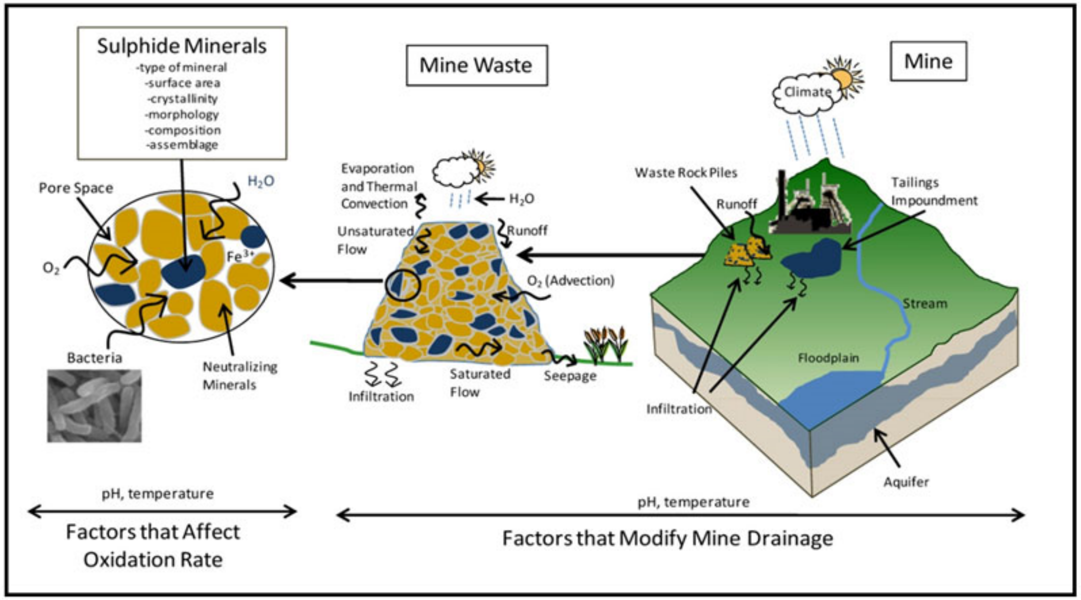
— HENRY MARSHALL TORY, FOUNDING PRESIDENT, 1908

- Formerly "Acid Mine Drainage" (AMD)
  - Not restricted to mines
- Weathering of sulfide minerals, particularly pyrite
  - Rio Tinto, Spain (photo)
  - Sulfur Creek,_____
- Global liability from ARD now exceeds $100 **B** (2011)
- West Virginia spends > $1M/day treating ARD

https://upload.wikimedia.org/wikipedia/commons/9/91/Riotintoagua.jpg

ARD results from physical, chemical, and biological properties occurring in combination:

- Surface area, grain size
  - Small grain size / high surface area reacts first
- Presence of: oxygen, water, oxidizers (iron), existing acidity, high temperature
- Ferroxidans bacteria



Kim Askew – Winter 2011 CIV E 682 Course Notes

- Iron sulphide (pyrite), FeS_2, is most common sulphide mineral
- To initiate pyrite oxidation, oxygen and water are needed:

1) $2FeS_2 + 2H_2O + 7O_2 \longrightarrow \underline{4H^+} + 4SO_4^{2-} + \underline{2Fe^{2+}}$

2) $\underline{4Fe^{2+}} + 10H_2O + O_2 \longrightarrow 4Fe(OH)_3 + \underline{8H^+}$

- Less oxygen required in (2), but more acidity produced
- (1) & (2) occur until pH ~4.5 when $2Fe^{3+}$ can remain in solution
- Abiotic until pH ~4.5

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2) $\underline{4Fe^{2+}} + 10H_2O + O_2 \longrightarrow 4Fe(OH)_3 + \underline{8H^+}$

3) $2Fe^{2+} + O_2 + 4H^+ \xrightarrow{\textit{T. Ferroxidans}} 2Fe^{3+} + 2H_2O$ pH < 4.5

4) $FeS_2 + 14Fe^{3+} + 8H_2O \longrightarrow \underline{15Fe^{2+}} + 2SO_4^{2-} + \underline{\mathbf{16H^+}}$ pH < 3.5

Reaction (3):

- Consumption of acidity, creation of reactive Fe^{3+} (ferric iron)
- Catalyzing bacteria require little oxygen, but speed up reaction by 5-6 orders of magnitude (i.e. x10,000 – x1,000,000 faster)

Reaction (4):

- Direct oxidation of pyrite when pH is low enough. FAST!
- Anoxic environment (possible even in tailings ponds)

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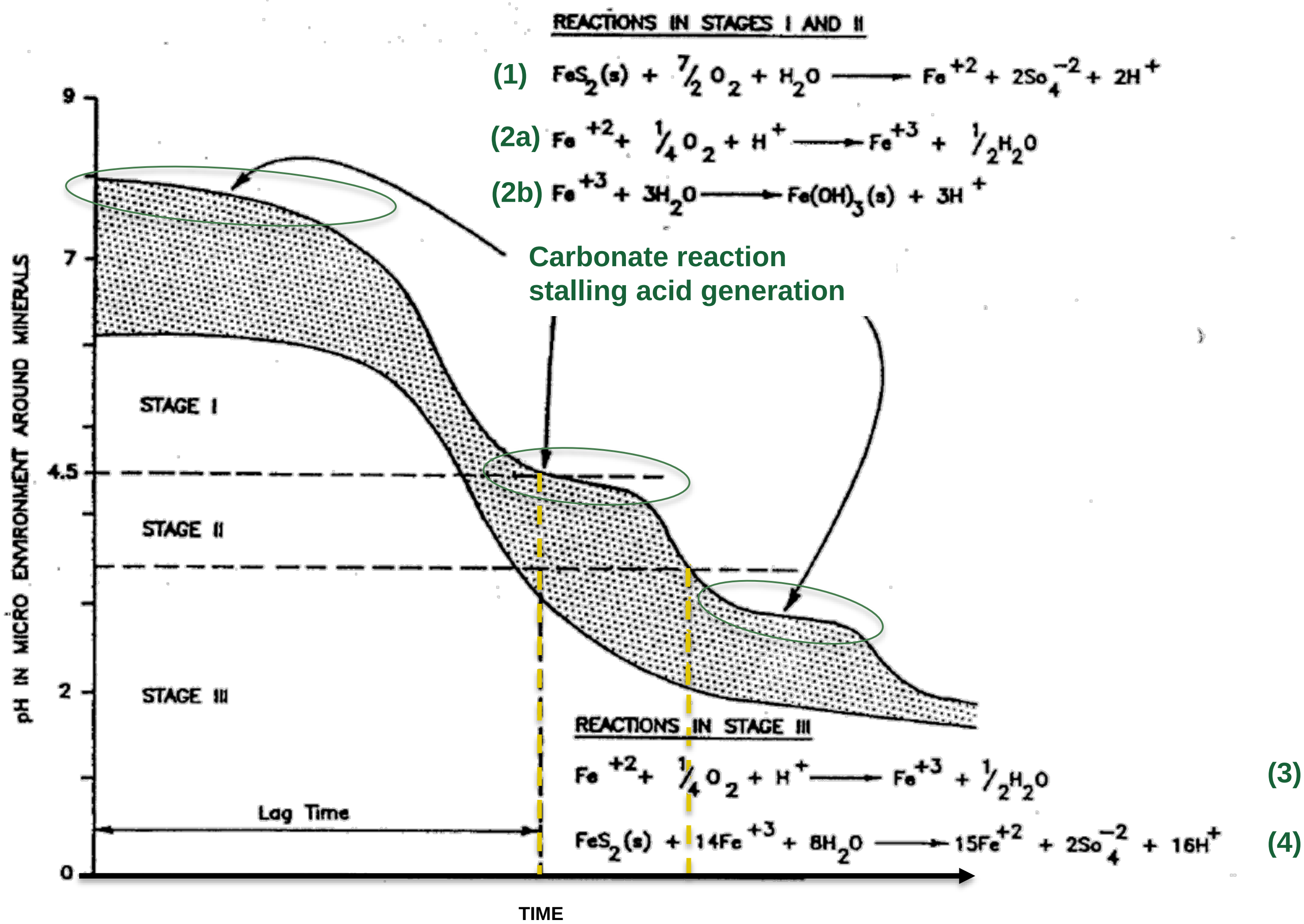
3) $2Fe^{2+} + O_2 + 2H^+ \xrightarrow{\textit{T. Ferroxidans}} 2Fe^{3+} + H_2O$

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

The cycle continues…

- Low pH water can be released to environment
  - Low pH water dissolves metals in exposed rock
  - Heavy metal toxicity in water
  - Sterilization of downstream land and water



Progression of Stages in Acid Generation with Time as a Function of pH
(Adapted from SRK, 1992)

Neutralization of acidic water:

$$MeCO_3 + H^+ \longrightarrow Me^{2+} + HCO_3^-$$

where Me = divalent cation (i.e. calcium, Ca^{2+}, manganese, Mn^{2+}, etc.)

Reclamation of acidic soil: ($CaCO_3$ example)

1. Consume protons

$$3CaCO_3 + 6H^+ \longrightarrow 3Ca^{2+} + 3CO_2 + 3H_2O$$

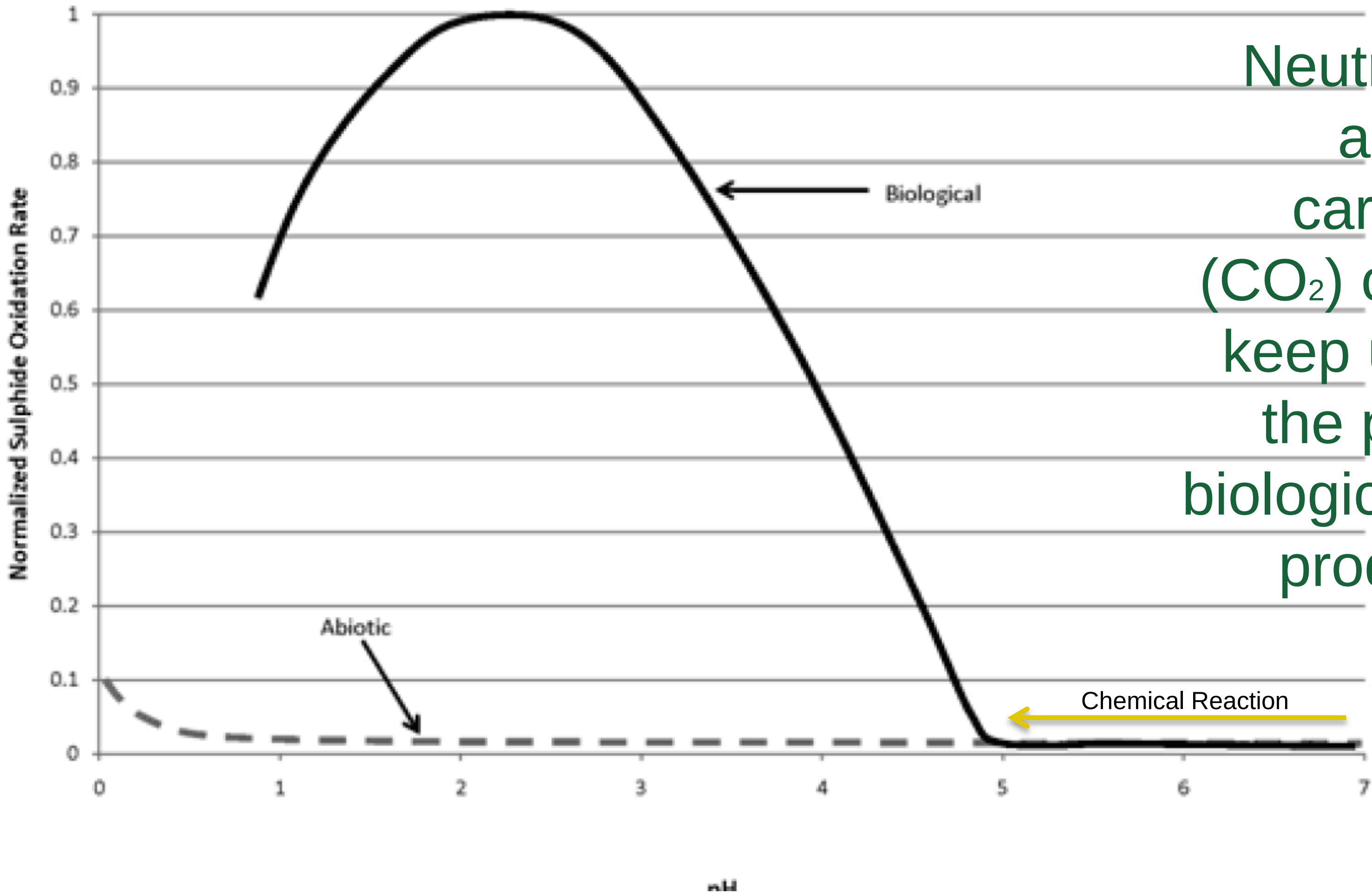
2. Exchange Al^{3+}

$$3Ca^{2+} + \underset{\text{(on surface)}}{Al_2} \longrightarrow \underset{\text{(on surface)}}{Ca_3} + 2Al^{3+}$$

3. Precipitate Al^{3+}

$$2Al^{3+} + H_2O \longrightarrow 2Al(OH)_3 + 6H^+$$

Overall: $$3CaCO_3 + Al_2 + 3H_2O \longrightarrow Ca_3 + 2Al(OH)_3 + 3CO_2$$



Neutralizing ability of carbonate (CO_2) can not keep up with the pace of biological acid production

Normalized Sulphide oxidation rates with and without bacterial mediation (from Robertson & Broughton, 1992)

Characterization:

- Site specific conditions always dictate
  - Potential for carbonate coating & isolation rendering them unreactive with acidity?
  - Already at a stage beyond effectiveness of carbonate?
- Site specific characterization is intended to answer the following:
  - Is ARD likely to occur?
  - What are ARD **sources**?
  - How much is likely to generate and when?
  - What **pathways** exist to transport contaminants to environment?
  - What **receptors** exist and what is the anticipated impact?
  - What methods of **prevention**, mitigation, or management exist?

Too late!

Geologic characteristics of the ore body and host rock define the chemistry of the surface water and runoff resulting from mining.

Characterization occurs progressively:

- Preliminary assessment can be attained from geologic and environmental data collected during exploration
- Primary **sources** and initial **receptors** can be identified as project develops
- Watershed scale hydrologic & hydrogeologic analyses determine quantity & direction of **pathways**, secondary receptors
- Continual data collection and analysis is required through mine life to update prevention techniques, monitor the environment, and measure impacts.

PROJECT LIFESPAN

Sources:

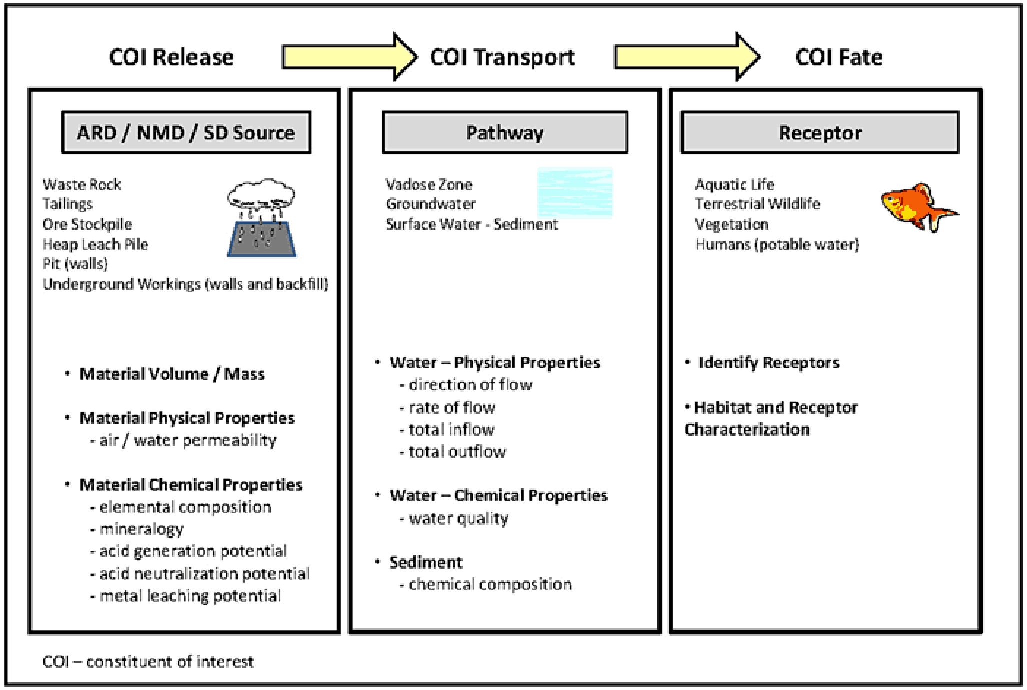
- Define source(s)
- Define quantity and quality of drainage
- *Typical: mine waste, ore, process waste, & open cuts*

Pathways:

- ID surface & groundwater pathways
- *Typical: water*

Receptors:

- Identify intermediary and ultimate receptors
- *Typical: water bodies*



1980 – 1994: Open pits (3) & small underground mine

- Closed due to resource depletion
- Copper, silver, & gold extracted
- Mill/ floatation circuit & a cyanide leach circuit
- ARD found soon after mine opened
- Large runoff managed while active

Post-Closure

- 2004: New high density sludge plant due to high runoff ($10 M)
- Sludge placed in abandoned pit
- 4 full-time staff
- Increased efforts, experiments

Goldcorp 2006 Closed Sites Sustainability Report

Pro-Active mitigation:

Three open pits

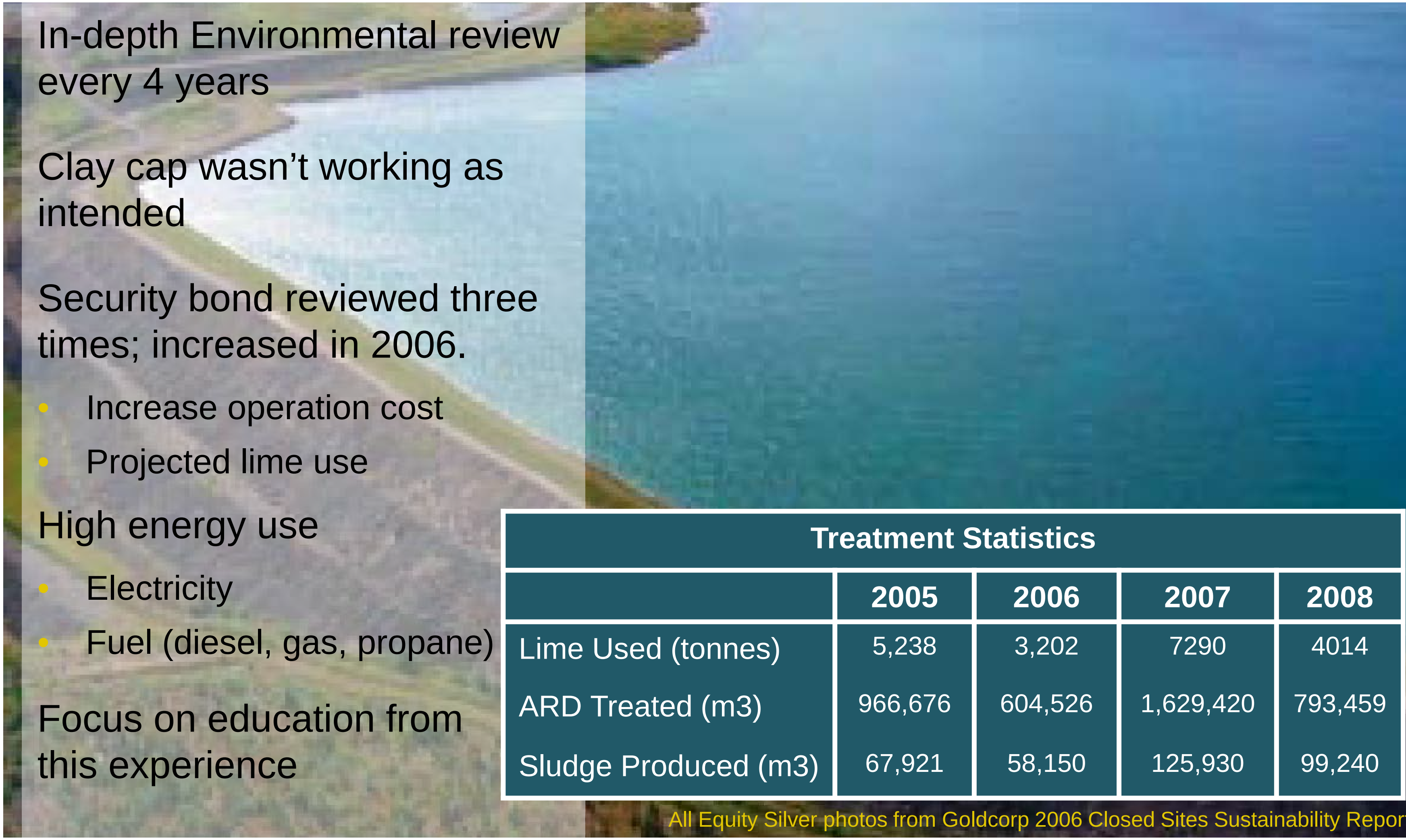
- 2 flooded
- 1 backfilled with mined PAF rock & sludge

Three revegetated waste rock storage areas

- Re-contoured
- Compacted clay cap (intended to reduce water & air infiltration)

Ongoing monitoring, assessment, adjustment

All Equity Silver photos from Goldcorp 2006 Closed Sites Sustainability Report



In-depth Environmental review every 4 years

Clay cap wasn't working as intended

Security bond reviewed three times; increased in 2006.

- Increase operation cost
- Projected lime use

High energy use

- Electricity
- Fuel (diesel, gas, propane)

Focus on education from this experience

Treatment Statistics				
	2005	**2006**	**2007**	**2008**
Lime Used (tonnes)	5,238	3,202	7290	4014
ARD Treated (m3)	966,676	604,526	1,629,420	793,459
Sludge Produced (m3)	67,921	58,150	125,930	99,240

All Equity Silver photos from Goldcorp 2006 Closed Sites Sustainability Report

Lab Static Methods: Acid-Base Accounting, ABA

- Calculates acid potential via proportion of acid generating and neutralizing material. Always do this.

Net Neutralizing Potential = NP - AP

Net acid producing potential = MPA - ANC

AP (acid potential): kg $CaCO_3$/tonne of rock, **or**

MPA (maximum potential acidity): kg H_2SO_4/ tonne of rock

NP (neutralization potential): total C, assumed as calcite, **or**

ANC (acid neutralizing capacity): kg $CaCO_3$/tonne of rock

- Rule of Thumb for soil:
  - 1 hectare acidic soil + 1 tonne lime = 0.1 pH increase
  - 2 – 3 times more NP than AP is generally “safe”

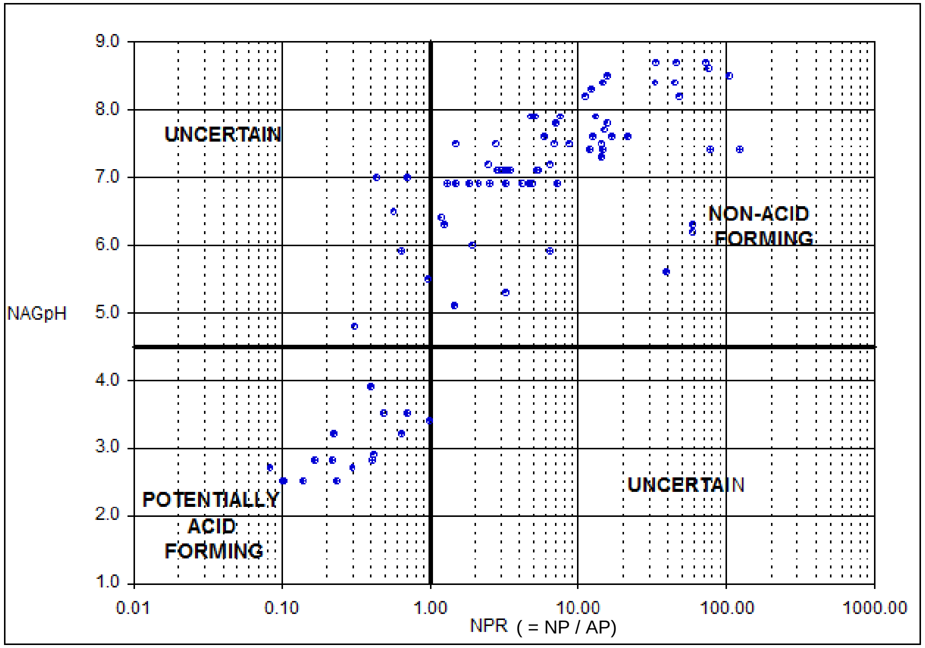
Just 2% sulphur is explosive in a waste rock pile!

Lab Static Tests: Net Acid Generation (NAG) & paste pH Tests

- One single value to determine acid potential
- **NAG pH:** Reacts a sample with hydrogen peroxide (H_2O_2) to rapidly oxidize
- Since neutralization and acid generation occur at the same time, the net result is representative of the total acid generated or total neutralizing potential

- **Paste pH:** mix a solid, oxidized sample with equal volume of H_2O, then measure pH.
  - Cheap, simple, and fast method!

- Combine static testing results to improve confidence in predictions & define ore cut-off criteria (GARD Guide):



Lab Static / Short Term Testing

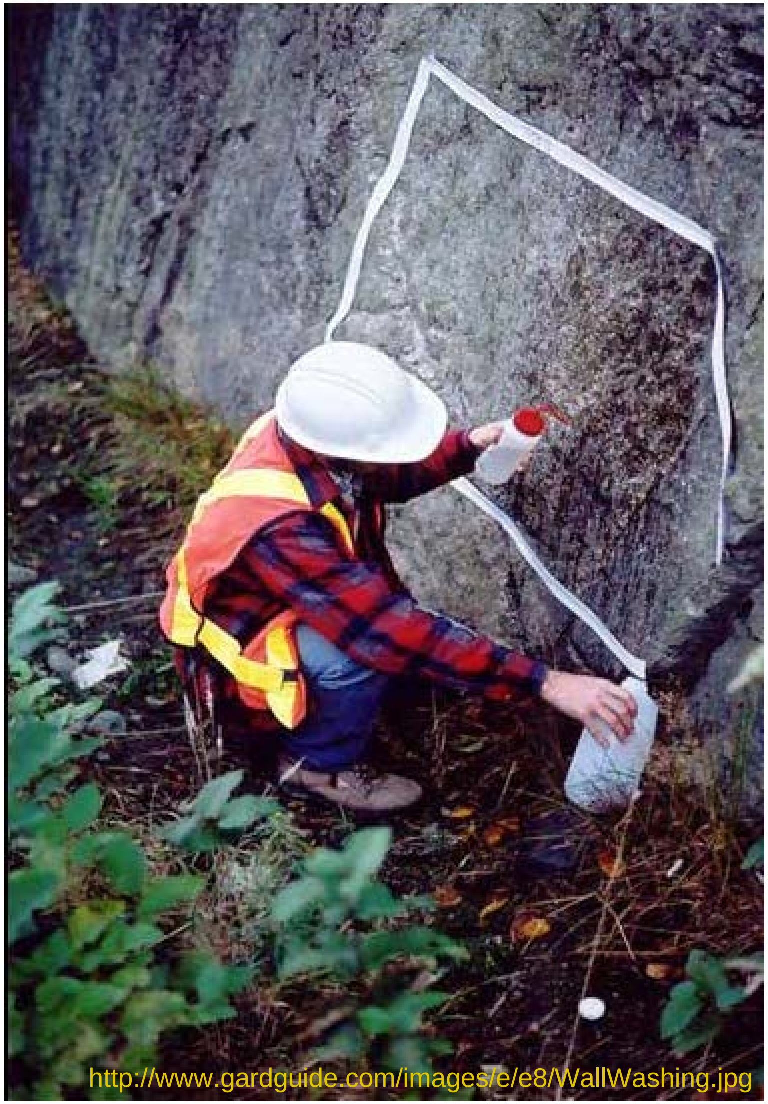
- Acid base accounting
- NAG pH
- Paste pH

Lab Kinetic Testing

- Leach samples; collect leachate after one week; test for metals and acidity; repeat.
- Slow, complicated test expedites oxidation.
- Humidity cell tests (ASTM D5744) or column tests (“barrel tests”)
- Column tests provide more range in testing degree of saturation

Field Testing:

- Field leaching test (Vary in scale. Replicate actual conditions but are slow)
- Wall washing (runoff quality testing from exposed portion)
- Large scale field programs



Test cells for waste rock

Grasberg, Indonesia

Paste tailings test plot,

Somincor Neves Corvo Mine, Portugal

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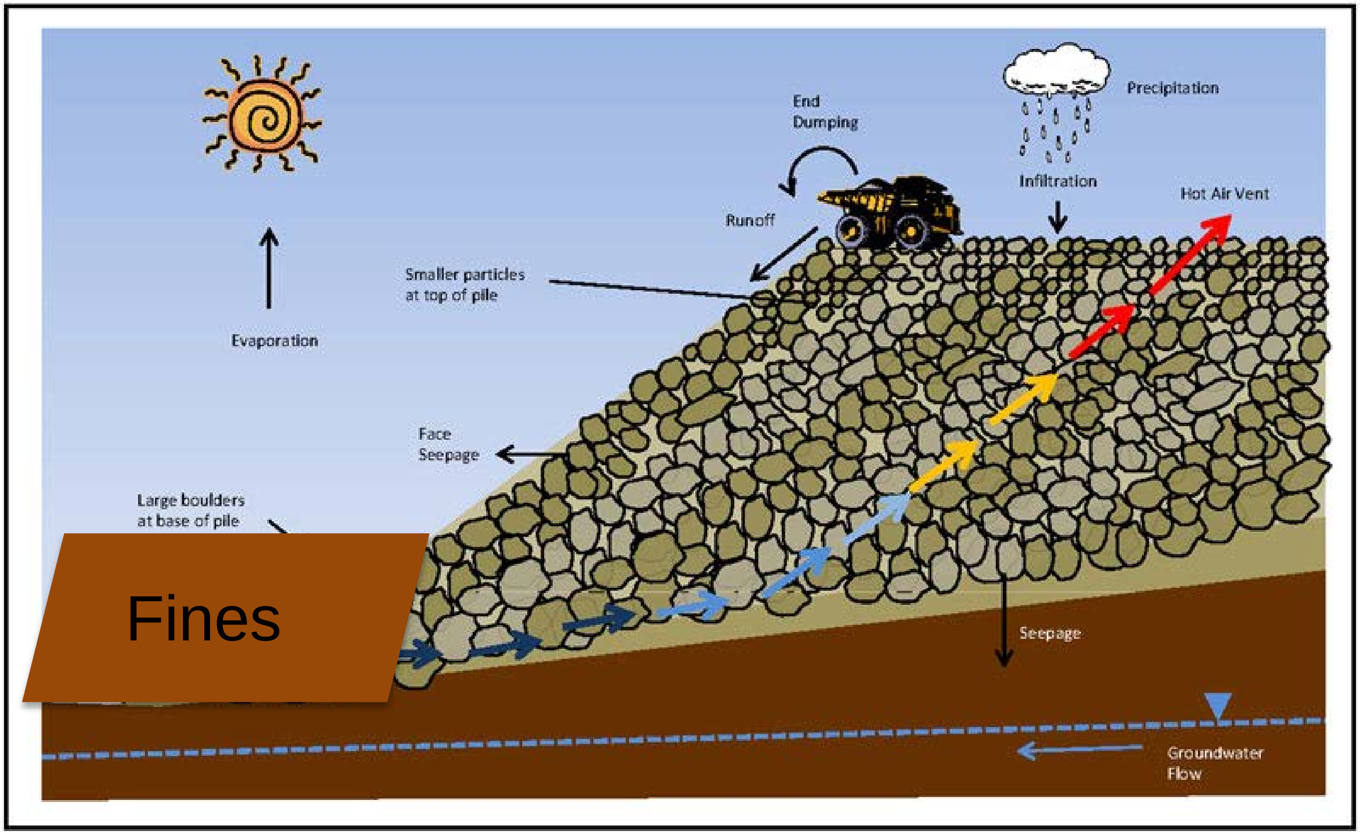
SCALE OF EXPERIMENT INCREASES

Prevention Methods: proactive avoidance of ARD requires early characterization and prediction, followed by integration of mine planning, waste management, and site design.

PNG example: area labelling to make operations' job easier.

< 0.3	0.3 - 4	> 4
To Embankment	Case by case basis	Tailings Impoundment

Prevention Method: Avoid creating “problem” structures. I.e. PAG rock in a waste rock dumps.



(Chapter 6, GARD Guide)

Mitigation Methods: reactive strategy to reduce the amount of ARD produced by restricting mineral oxidation.

- Once ARD process is started, it is difficult to stop
- Can be very expensive and continue for extended time frames
  - Expensive preventative measures may be cheaper than long-term water treatment & mitigation over the long-term.
- Realistic methodology only for exhausted or legacy sites
- Challenge in waste storage:
  - Geotechnical stability: well-drained, unsaturated, stable (ie. waste rock dump)
  - Geochemical stability: undrained, fully saturated, no oxygen available for oxidation (i.e. tailings pond)
- Understand physical and chemical processes, and climate (what works in a dry climate, may not in a wet/humid climate)

ACID ROCK DRAINAGE – WHEAL JANE TIN MINE, CORNWALL, UK

Open sporadically from the 1800’s

1992: Closed permanently

1992/93: Drainage systems overtopped

1994: Constructed settling ponds & water treatment facility

2002: water treatment cost exceeds £20 million

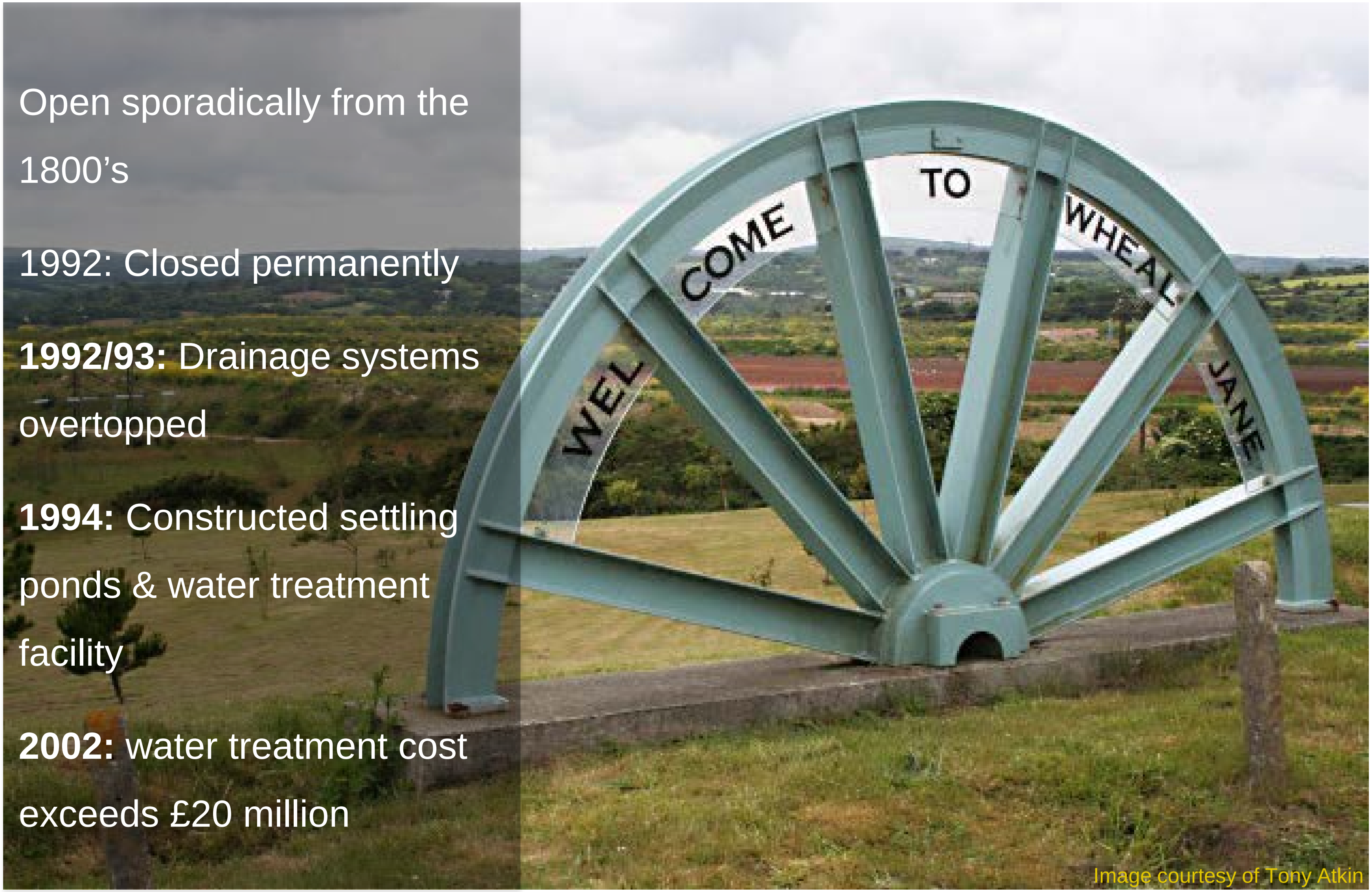


Image courtesy of Tony Atkin

ACID ROCK DRAINAGE – WHEAL JANE TIN MINE, CORNWALL, UK

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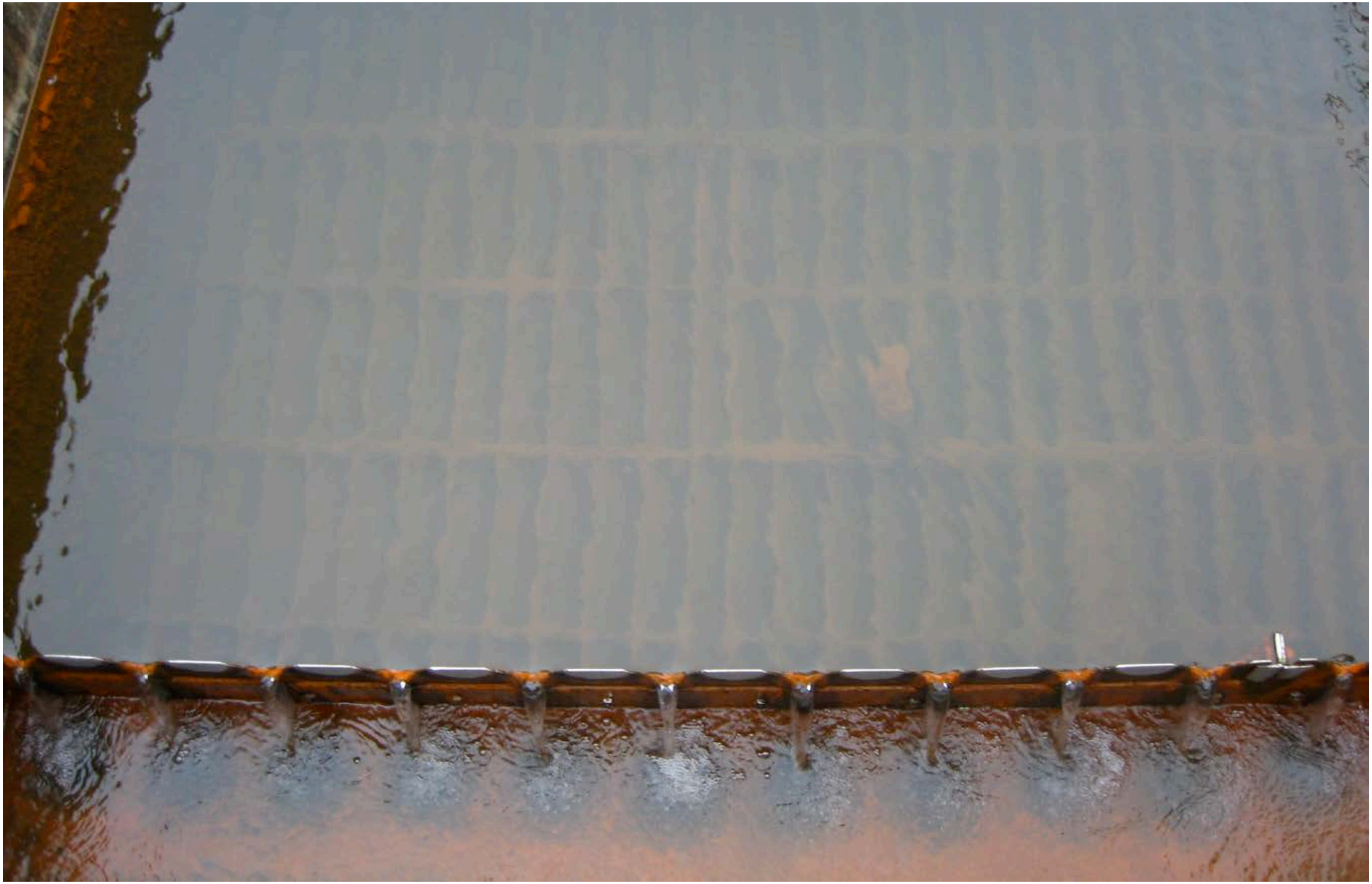

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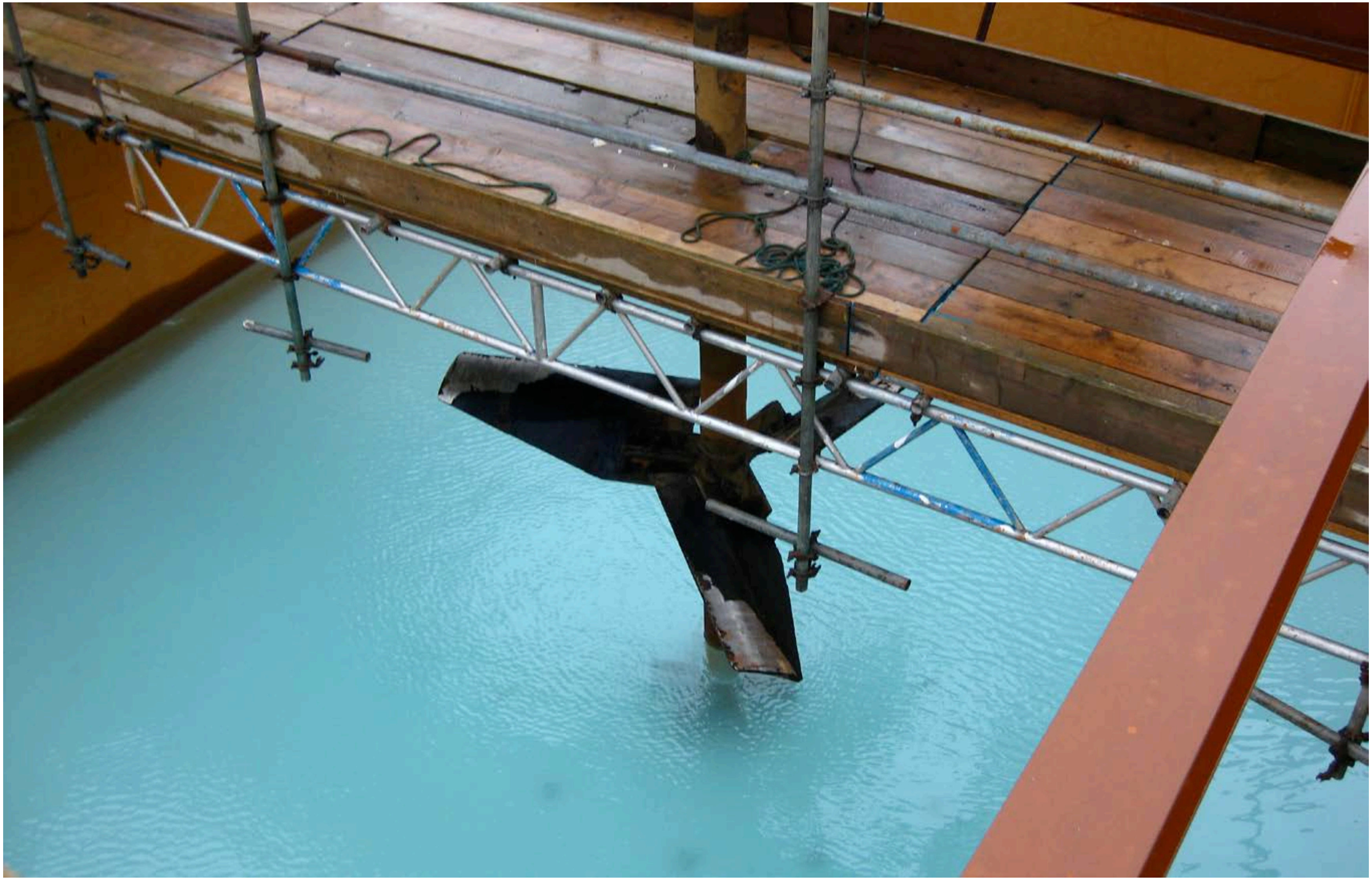

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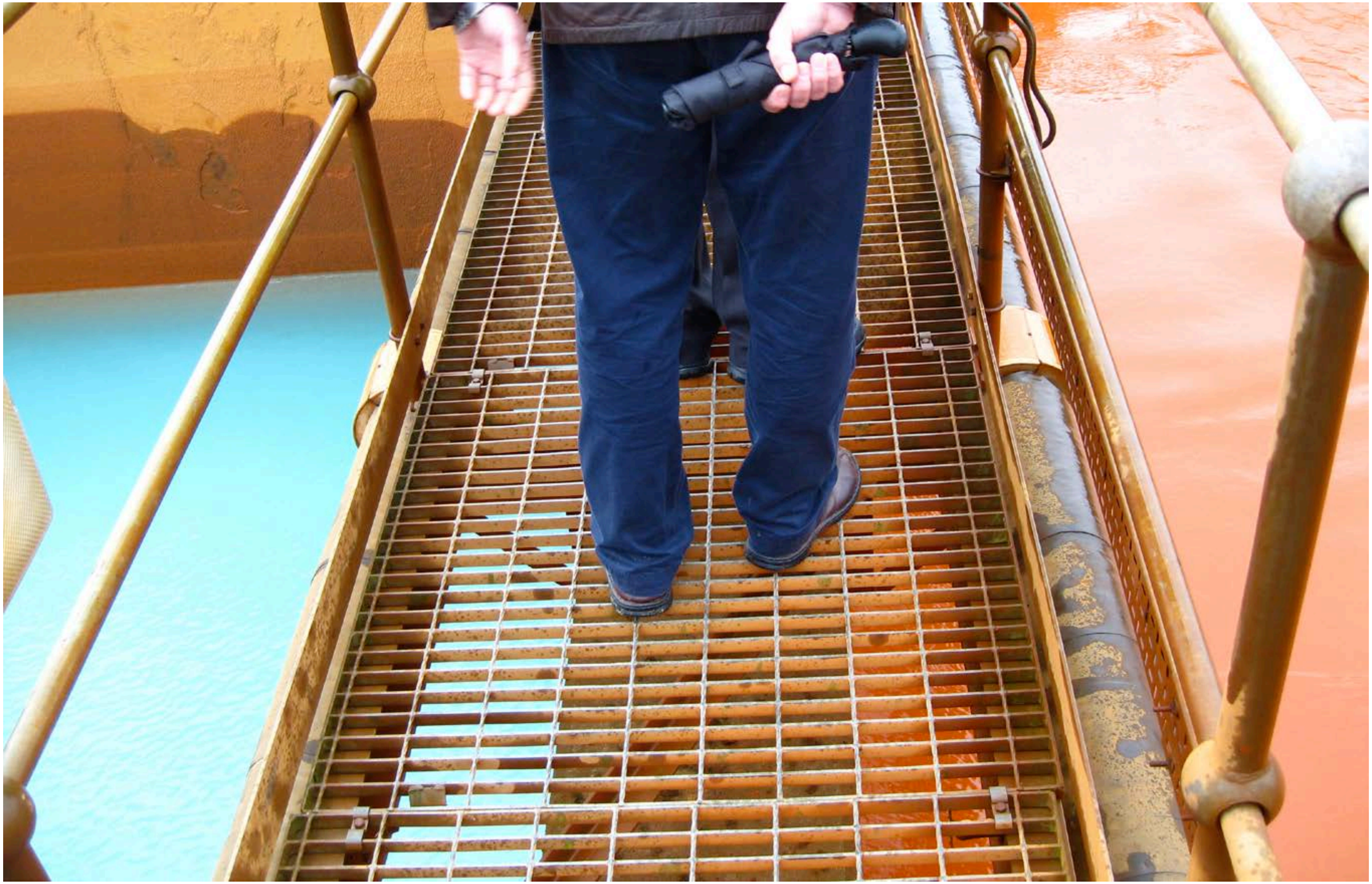



Post-treatment
Sludge
Pre-treatment ARD

Final product: pH 9.3

Discharged to +/- pH 5 river

Improves overall water quality in area

Expensive, staff in perpetuity

Good mitigation, but pre-planning can avoid these costs

Site turned into Geo-consultant & sustainability hub

Best Practices:

- Re-mining legacy sites
- Special handling built into mine plan (backfilling voids, subaqueous deposition, etc.)
- Segregation (PAG vs. NAG material)

Waste Rock

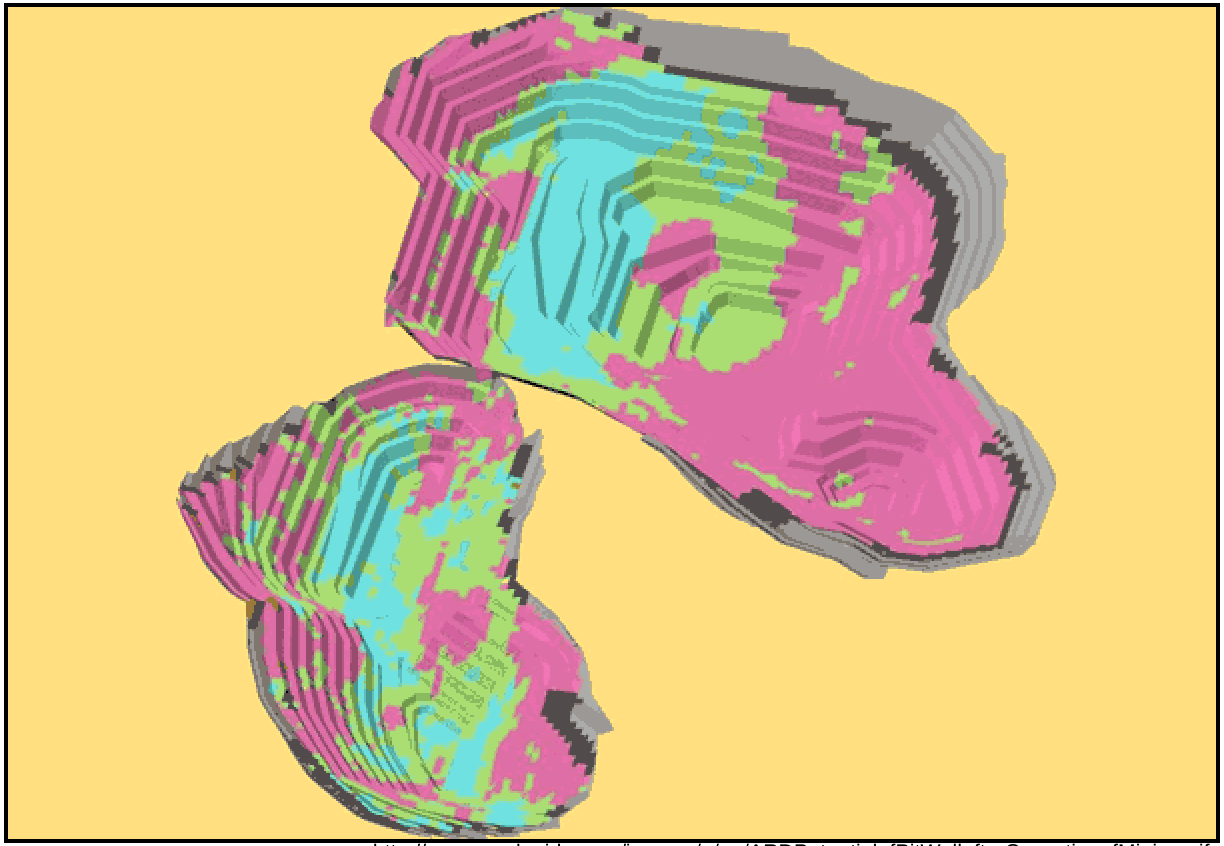
- Tailings desulfurization (Detour Gold, ON)
- Physical tailings conditioning (reduce oxygen diffusion & increase water retention via thickening, compaction, etc.)
- Encapsulation / Layering
- Intimate blending (homogenous deposit of AP & NP tailings)
- Covers (flat)

Tailings

- Co-disposal
- Permafrost / Freezing (-8 C mean air temp. required)

Both

Best Practices:



http://www.gardguide.com/images/e/ee/ARDPotentialofPitWallafterCessationofMining.gif

Best Practices: Additives & Amendments ($$$) / "Chemical Tailings Conditioning"

Passivation: induce a reaction that builds an inert, protective layer on PAF rock surfaces. Generally long term solution.

Alkaline materials: add alkaline amendment and mix intimately.

Organic matter: this inherently has high pH, and organic matter will consume oxygen and promote metal reduction.

Bactericides: killing the bacteria that rapidly expedite ARD generation will slow the process to a point where it can be managed with blended carbonates alone.

Cover systems:

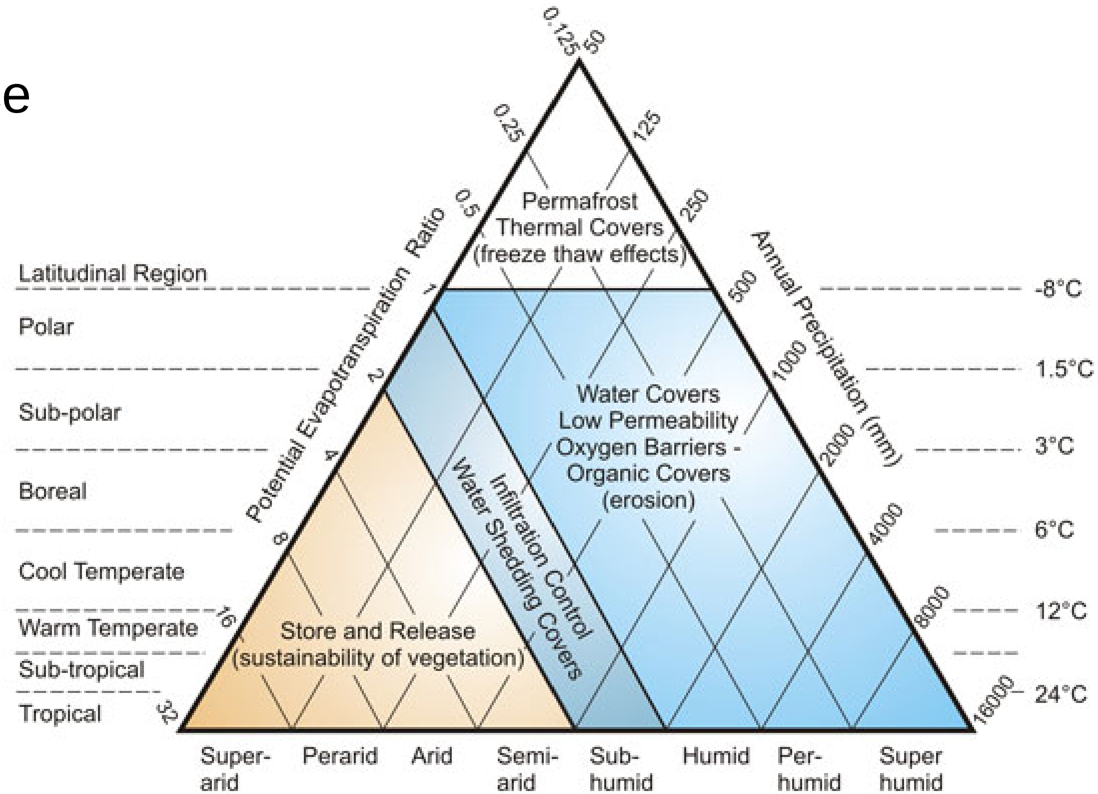
Increasing complexity:

+ increased performance

- increased cost &

- difficulty to construct

Keep it simple!



http://www.gardguide.com/images/a/a5/CoversandClimateTypes.jpg

In Summary:

1. **Identify** where sulfide-rich rock is likely to develop ARD
   - Lab tests do a good job of predicting total ARD potential, but not the rate
2. **Prevent**
   - Via waste management, mine planning & design
3. **Mitigate** (ongoing monitoring required, $)
   - Restrict oxygen diffusion and moisture ingress
   - Alter chemistry to neutralize acid
4. **Treat** (ongoing treatment required, $$$ + liability)
   - Collect acidic runoff / effluent and treat
   - Account for waste products of treatment, if they exist

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