

# Wastes of the Mining Industry

What mining leaves behind, and what to do about it

**By the end of this session, you will know:**

- What mine waste is, and why mining produces so much of it
- How tailings are stored, and why storage facilities fail
- How acid mine drainage forms, and how it is predicted and treated
- When mine waste stops being a liability and becomes a resource

Click to start



# How to study this DTM

## Your path through the DTM:

1. Start at the main hub and click an item to see its details.
2. Use the Return buttons to jump back to a hub at any time.
3. Open another hub to explore the topic from a new angle.
4. Click an item to open its detailed profile page.
5. Visit each content hub to explore the full topic.
6. Finish with the Key Takeaways.

Click to start



### Time needed

About 40 minutes in total

### Target group

Secondary level, beginner

### Format

Interactive self-study

### How to explore

Use the hubs to explore the topic and answer the guiding questions.

### Files

Interactive slides and quiz  
(NEXPERT website)

# Maarmorilik, 1975: ore ship blockade

For 17 years, Black Angel mined above a West Greenland fjord. Its waste stayed behind.

- Ore crossed the fjord on a 1.5 km aerial tramway.
- Waste rock was tipped into the tidal zone.
- Tailings went straight into the fjord.
- Lead and zinc contaminated water, sediment and marine life.
- In 1975, seal hunters blockaded an ore ship.



Maarmorilik and the tramway to the mine

## Black Angel in figures

|           |                                    |
|-----------|------------------------------------|
| Operated  | <b>1973 to 1991</b>                |
| Ore mined | <b>11.2 Mt</b>                     |
| Grades    | <b>4.1 % lead, 12.6 % zinc</b>     |
| Place     | <b>Maarmorilik, West Greenland</b> |

**The mine closed in 1991. The waste stayed.**

This DTM is about what a mine leaves behind, and about what can still be done with it.

Click to continue



# Every mine is also a waste factory

By mass, mining moves far more waste than metal.



Open pit and waste rock dumps, Ernest Henry, Australia

## Waste is unavoidable

Ore holds a few percent of the metal we want. Everything else has to go somewhere.

## Waste is not automatically dangerous

Risk comes from the minerals, the water and the way it is stored.

## What we do with it is a choice

Waste can stay a hazard, become a landscape, or become an ore deposit.

## Four steps through the topic

What the waste is, where it is stored, how it turns acid, and how it becomes a resource again.

Click to continue



# Mine Waste: the main hub

Mining moves more rock than all natural erosion on Earth, and almost all of it becomes waste.



**What is  
mine waste?**



**Tailings and  
dam safety**



**Acid mine  
drainage**



**From liability  
to resource**



Click a box to explore that topic.

**Skip to key takeaways**

# What is mine waste?

A: Mine waste

Mining, processing and smelting each leave their own waste stream.

**Three kinds  
of waste**

**The scale of  
the problem**

**From ore  
to waste**

**Waste rock,  
tailings, slag**

**Mine water**

**Greenland:  
Black Angel**



Click a card to open it.

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# Three kinds of waste

A: Mine waste

Mine wastes are the unwanted by-products of mining, processing and metallurgy.

## Mining wastes

Overburden and waste rock  
Mining water  
Dust and gases

## Processing wastes

Tailings  
Sludges and mill water  
Dust

## Metallurgical wastes

Slag and roasted ore  
Flue dust and ash  
Leached ore

Ore or waste? The cut-off grade decides

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# The scale of the problem

A: Mine waste

Mining moves more material than every river, glacier and wind on the planet combined.

**25 Gt**

of solid mine waste every year

**50 Gt**

expected per year by 2050, as ore grades keep falling

**2000 km<sup>3</sup>**

of mine waste over the next hundred years

## US EPA, 1987

“Problems related to mining waste may be rated as second only to global warming and stratospheric ozone depletion.”

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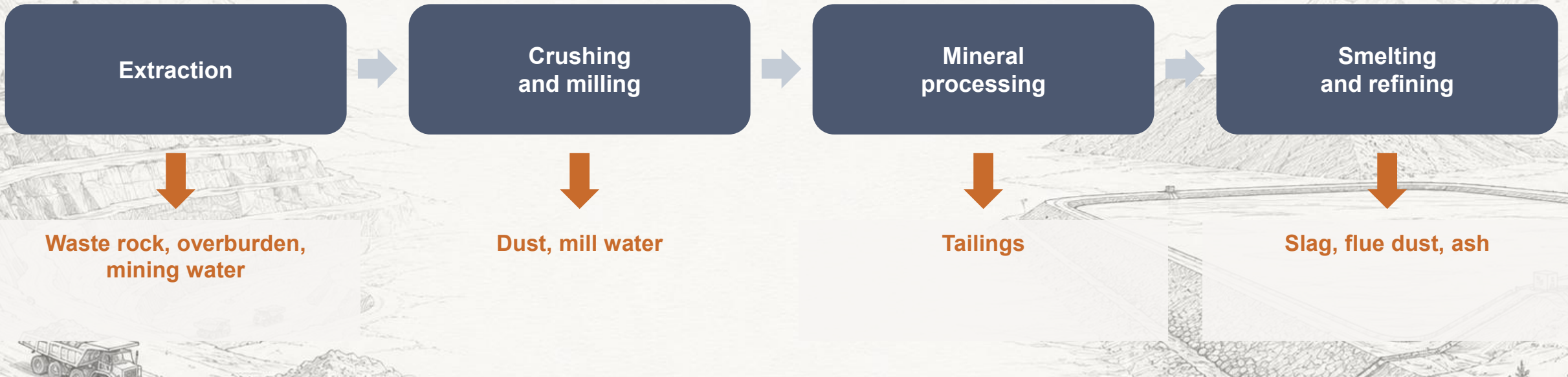


Waste rock dumps and tailings of a historic mine site

# From ore to waste: follow the rock

A: Mine waste

Follow the rock: every step of the chain produces its own waste stream.



**1 tonne of ore at 0.6% copper**

6 kg copper → 994 kg waste

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Three waste streams, three different problems.

|               | Waste rock                  | Tailings                     | Slag                |
|---------------|-----------------------------|------------------------------|---------------------|
| What it is    | Rock moved to reach the ore | Ground residue of processing | Residue of smelting |
| Grain size    | Blocks to gravel            | Sand to clay, below 2 mm     | Coarse and glassy   |
| Where it goes | Dumps and heaps             | Tailings storage facilities  | Slag dumps          |
| Main concern  | Acid drainage, erosion      | Dam failure, seepage, dust   | Metal leaching      |

**Counter-intuitive but true**

Tailings usually leach less than the waste rock from the same deposit, because their fine, uniform grains let less oxygen and water through.

Water that has touched a mine is mine waste, whatever it looks like.

## Mining water

In contact with the mine workings.

## Mill water

Used to crush and size the ore.

## Process water

Used in hydrometallurgical treatment.

## Leachate

Percolated through solid mine waste.

## A burden and a resource at the same time

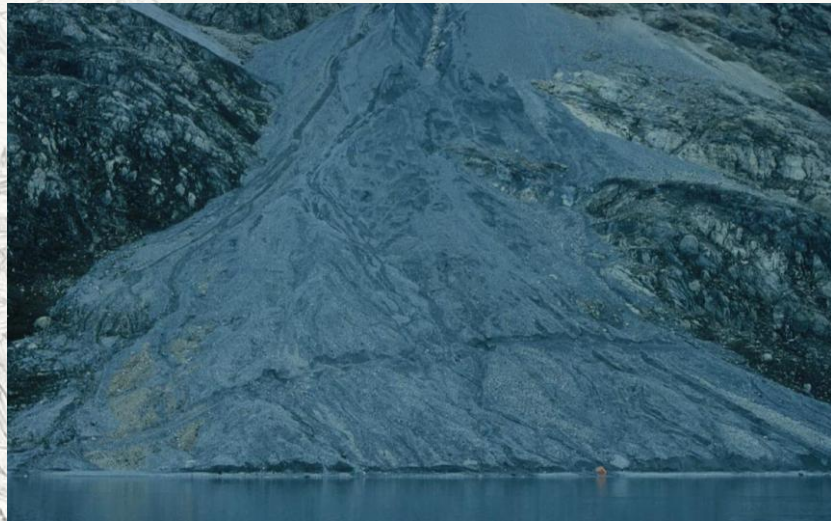
Mine water must be pumped, treated and discharged within limits. It is also needed for processing, dust control and rehabilitation.

See how water turns acid

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Black Angel, Maarmorilik: the same rock, two very different decades.



Waste rock tipped into the fjord at Maarmorilik

## What happened

Waste rock was tipped over the cliff into the tidal zone.

Tailings went straight into the fjord.

Lead and zinc rose in water, sediment, seaweed, mussels and fish.

In 1975 seal hunters blockaded an ore ship in protest.

## What changed

Authorities intervened while the mine still operated.

The waste pile was moved out of the tidal zone.

The metal content of the tailings was cut sharply.

By 2010 water samples met EU drinking water standards.

## Worth thinking about

Exploration around Maarmorilik continues and ore remains in the mountain. What should a future permit demand?

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**The cut-off grade is the lowest metal content that can be mined at a profit.**

Rock above it is ore. Rock below it is waste.

The line is not fixed. It moves with metal prices, technology and costs.

When prices rise or processing improves, yesterday's waste can become ore.

[Return to Three kinds of waste](#)



The largest and riskiest waste stream on any mine site.

**What tailings  
are made of**

**The biggest  
footprint**

**Three ways to  
build a dam**

**Why dams  
fail**

**Brumadinho  
2019**

**A timeline  
of failures**

**Beyond  
the dam**

**The arctic  
question**

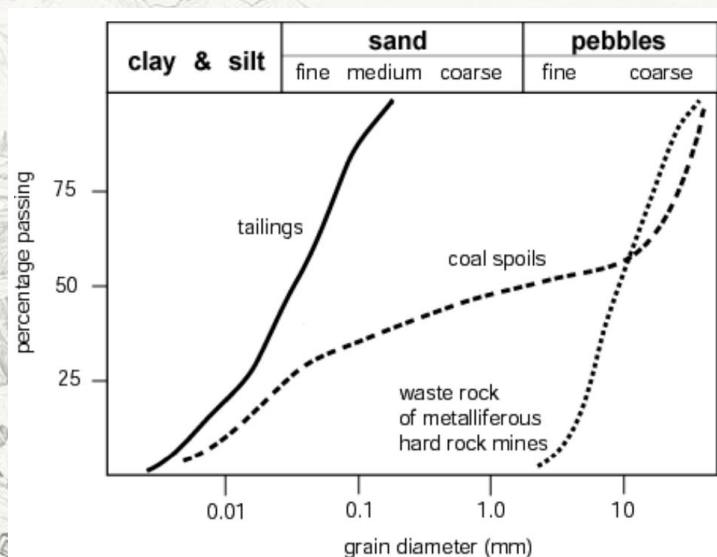


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Tailings are the ground residue of processing. By mass they equal the ore that was mined.



Particle size curves, after Lottermoser (2010)

## Why the grain size matters

Tailings are far finer than waste rock. Fine, uniform grains hold water and behave like a liquid when shaken, which is what makes a tailings facility an engineering structure.

## What tailings consist of

Process chemicals: flotation reagents and oxidants, partly recycled with the water.

Tailings liquid: process water plus rainwater, often saline and sometimes acid.

Tailings solids: ground gangue, roughly 70 to 80 percent sand and the rest clay.

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# The biggest footprint on any mine site

The tailings facility is normally the largest structure on a mine site.

3 km

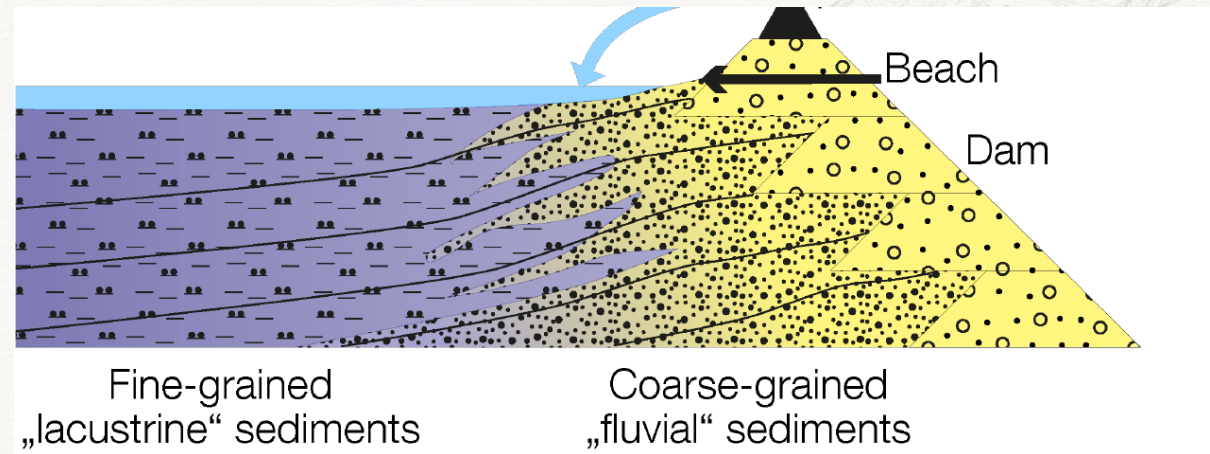
of dam at Copper Mountain, Canada

255 m

dam height there, raised in stages over decades

130 Mt

at Kidd Creek, stacked with no embankment because the ground was too weak



Coarse sand settles near the discharge point, fine clay furthest away

## A tailings facility is never finished

Unlike a water dam it is raised throughout the life of the mine, and then has to hold indefinitely.

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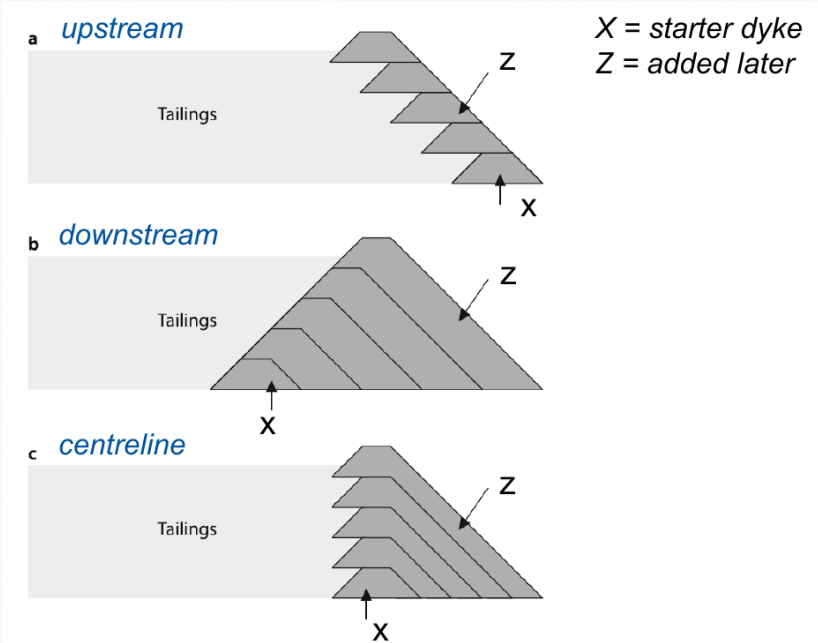


# Three ways to build a dam

Dams are raised in stages. The direction of raising decides how safe they are.

|            | Share       | Cost     | Seismic safety |
|------------|-------------|----------|----------------|
| Upstream   | >50%        | Low      | Poor           |
| Centerline | Less common | Moderate | Fair           |
| Downstream | Less common | High     | Good           |

The crest of an upstream dam moves out over the tailings it is meant to retain. A downstream dam grows away from the pond, which costs far more material.



## The cheapest option fails most often

Upstream raising sits on soft, waterlogged tailings.

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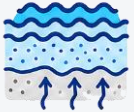


# Why tailings dams fail

At least two tailings dams fail every year. More than 250 have failed since the 1950s.

## Liquefaction

Saturated tailings lose strength and flow.



## Raised too fast

Pore pressure cannot dissipate.



## Foundation failure

Weak ground gives way.



## Overtopping

Water rises above the crest.



## Seepage

Flow erodes the dam internally.



## Failures rarely have a single cause

Most collapses combine several of these mechanisms, which is why monitoring covers the dam, the impoundment and the environment at once.

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# Case study: Brumadinho, 25 January 2019

B: Tailings

25 January 2019, Brumadinho, Brazil. An upstream dam failed without warning.

**270** people died, most of them at work below the dam

**12 Mm<sup>3</sup>** of tailings released in minutes

## What made it so deadly

The inactive dam was still full.  
Liquefaction turned tailings into a fast flow.  
Workplace buildings stood directly below it.

## What changed afterwards

Brazil ordered upstream dams to be decommissioned.  
The 2020 global standard set a benchmark for safer design, governance and disclosure.  
Investors demanded disclosure.

## The uncomfortable lesson

A dam that no longer receives tailings is not a dam that is safe.

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[How the dam failed, step by step](#)

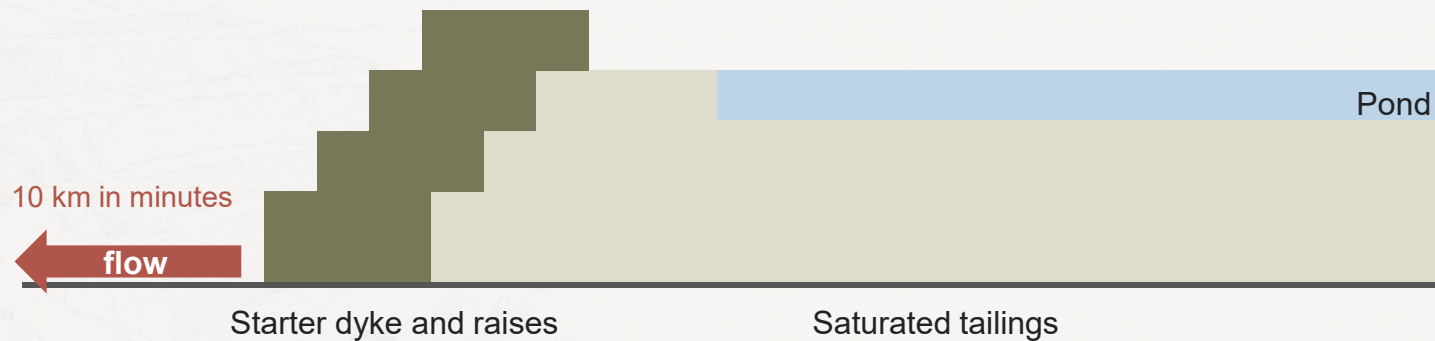


# Info: how the Brumadinho dam failed

## B: Tailings

The dam had been raised in stages on its own tailings, and had taken no new material since 2016.

**Every raise stands on soft tailings, not rock.**



### 1 Water stays in

Fine tailings hold water for years. The mass stays saturated long after deposition stops.

### 2 Strength is lost

A small disturbance raises the pore pressure. Saturated tailings then lose their strength almost at once.

### 3 It flows

The material behaves like a liquid and leaves the impoundment in minutes.

### Closed does not mean safe

The dam had been inactive for three years. Liquefaction needs saturated material and a trigger.

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Five failures that shaped how the industry thinks about tailings.

| Year / site       | Failure                | Impact                          |
|-------------------|------------------------|---------------------------------|
| 1985 Val di Stava | Drainage failure       | 268 deaths                      |
| 2010 Ajka         | Red-mud basin breach   | 10 deaths; >1 Mm <sup>3</sup>   |
| 2014 Mount Polley | Weak foundation        | 14.5 Mm <sup>3</sup> to lake    |
| 2015 Mariana      | Liquefaction           | 19 deaths; 43.7 Mm <sup>3</sup> |
| 2019 Brumadinho   | Inactive dam liquefied | 270 deaths; ~12 Mm <sup>3</sup> |

## Five cases, three recurring causes

Water mismanagement, weak foundations and upstream construction recur across decades.

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Alternatives can reduce risk - or shift it elsewhere.

## In-pit disposal

Tailings go back into a mined out pit.

## Paste backfill

Thickened tailings returned underground.

## Riverine and marine

Released into a river or piped into deep water. Both are contested.

## Dry stacking

Filtered and stacked as a solid. No pond, no liquefaction.



Dry stacking at La Coipa, Chile

## Challenges

Filtering and transport use more energy and cost more than pumping. The trade-off: higher operating cost, lower long-term liability.

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In the Arctic the fjord has often looked like the easiest place to put tailings.

## Why it is attractive

Deep water close to the plant, no dam to maintain.  
No liquefaction risk and no long term dam liability.  
Permafrost and steep terrain limit the land options.

## Why it is contested

Metals enter the food chain.  
Effects are hard to monitor and impossible to reverse.  
Currents spread impacts across borders.

## The Greenland evidence

At Maarmorilik metal levels in mussels were still elevated in 2010. At Ivittuut waste rock affected 32 km of coastline and was still releasing lead and zinc in 2014.

## Before the next permit

Who should decide where tailings go, and how long should the operator stay responsible?

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Sulfides, water and oxygen create acid - a costly long-term legacy.



**The AMD engine**



**Acid made,  
acid consumed**



**The pH  
scale**



**Field  
indicators**



**Predicting  
AMD**



**Preventing  
AMD**



**Treating  
the water**



**Greenland:  
Ivittuut**

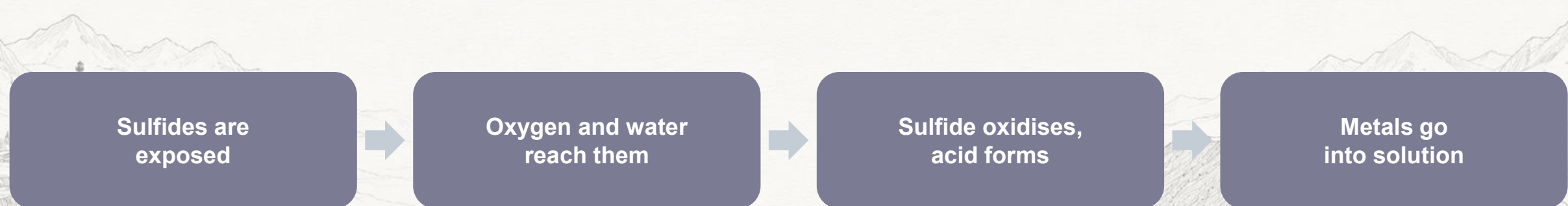


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Exposed sulfides react with air and water to form acid.



**Sulfides + oxygen + water → acid + dissolved metals**

## What makes it run faster

Surface area above all: a one centimetre pyrite cube has 6 square centimetres of surface, but ground to one micrometre grains the same volume has 6 square metres.

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Acid risk depends on the balance between acid generation and neutralisation.

## Reactions that produce acid

- Oxidation of pyrite and other iron sulfides
- Dissolution of soluble metal sulfate salts
- Hydrolysis of dissolved iron and aluminium

## Reactions that consume acid

- Dissolution of carbonates, by far the most effective
- Dissolution of silicates and adsorption onto clays
- Precipitation of soluble metal sulfates

## The balance can take years to tip

Carbonates buffer the acid until they are used up. A waste that looks harmless for a decade can still turn acid later, which is why prediction beats observation.

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# Reading pH: the acid scale

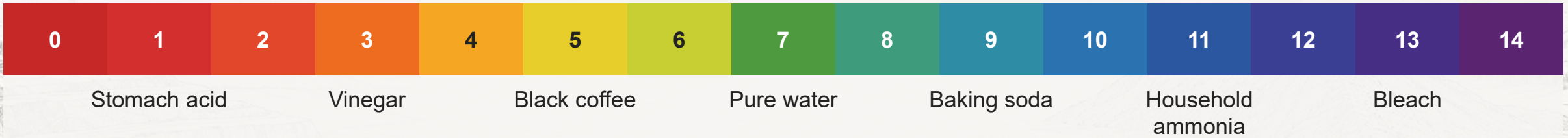
C: AMD

pH runs from 0 (acidic) to 14 (alkaline).

More acid

Neutral

More alkaline



## Where mine water sits

AMD is usually pH 2-4; severe cases fall below 1. Metals stay dissolved and move downstream.

## What normal water looks like

Streams and lakes are usually pH 6.5-8.5; clean rain is about pH 5.6.

## One step is a factor of ten

Each pH step is a 10× change. pH 3 is 10× more acidic than pH 4 and 100× more acidic than pH 5.

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Before any laboratory work, the site itself tells you a great deal.

## What you can see and smell

- A sulfurous smell around the waste
- Yellow to red staining from iron minerals
- Mineral salts blooming on the surface
- Bare ground, or unusual plant communities
- Orange coatings on the stream bed

## What needs an instrument

- pH below 5.6, or falling over time
- Rising conductivity, sulfate and metal loads
- Rising waste temperature
- Falling oxygen in the pore gas



Rio Tinto, Spain

## Colour is evidence, not proof

Orange staining shows iron precipitating as pH rises. Clear water can still be strongly acidic.

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# Can we predict it? Acid base accounting

C: AMD

Acid base accounting compares how much acid a rock can make with how much it can neutralise.

## MPA

**Maximum Potential Acidity**

Sulfide sulfur (%)  $\times$  30.6

## ANC

**Acid Neutralising Capacity**

from carbonate content or titration

## NAPP

**Net Acid Producing Potential**

MPA minus ANC. Positive means acid forming

## Classifying the waste

PAF = potentially acid forming: positive NAPP and net acid generation pH < 4.5. NAF = non-acid forming.

## Worked example

2% sulfide sulfur can produce 61.2 kg acid per tonne. If neutralising capacity is lower, the rock is acid forming.

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Prevention means interrupting the reaction: keep out water, keep out oxygen, or move the sulfides.

## Wet cover

Air contains about 35× more oxygen than saturated water.

Works with reliable water cover: ponds, wetlands or flooded pits.

Fails if the cover dries.

## Dry cover

Low permeability means water passes slowly, limiting water and oxygen.

Design: one clay-rich layer → layered barriers and drainage.

Failure: surface erosion, roots or animal burrows.

## And three more measures

Blending with alkaline material, encapsulating reactive waste in inert rock, and selective handling so that acid forming rock never reaches the surface pile.

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Once the water is acid it has to be collected and treated, often for a very long time.

## Active treatment

Continuous dosing with reagents, most often lime.

Metals precipitate and leave as sludge.

Effective and fast, but the cost never stops.

## Passive treatment

Little or no reagent, no mechanical equipment.

Aerobic wetlands for alkaline water, anaerobic for acid water.

Needs water all year, or it flushes at the next rain.



Acid drainage, Rio Tinto

## And the water you cannot see

Acid drainage reaches groundwater more often than surface water. The options are pump and treat, or a permeable reactive barrier in the flow path.

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Ivittuut supplied cryolite from 1859 until 1987. The mine is gone. The drainage is not.

## What happened

Mineralised waste rock was left where it lay.  
Zinc and lead drained into the Arsuk Fjord.  
About 32 kilometres of coastline were affected.  
In 2014 the rock was still releasing metal.

## Compare with Black Angel

There, regulators intervened while the mine still ran.  
The waste pile was moved and the tailings cleaned up.  
Contamination fell during operation and after closure.

## What both sites teach

Waste rock does not become safe by being abandoned. The cost of doing nothing is simply paid later, by someone else.

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Closure, rehabilitation and re-mining decide what a mine finally leaves behind.



**Closure starts  
on day one**



**Rebuilding a  
landscape**



**Sudbury  
regreening**



**Eden  
Project**



**Yesterday's  
waste,  
today's ore**



**Tailings as a  
carbon sink**



**Who sets  
the rules?**



Click a card to open it.

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Closure is not the last phase of a mine. It is a plan that exists before the first hole is drilled.

The site is divided into domains, and each one is closed differently

## Open pits

Model the future water, shape a safe landform

## Underground

Seal the portals, limit acid water

## Waste rock

Cover it, stop water ponding on top

## Tailings

Cover the residue, secure the structure

## Soils

Remove or treat, then import topsoil

## Buildings

Keep, sell, salvage or demolish

## Why plan this early

A well planned closure is cheaper, and rehabilitation can happen progressively instead of all at once.

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Returning a site to what it was is usually impossible. The realistic goal is safe, stable and useful.

## Three steps, in this order

1 Shape stable drainage → 2 Build soil → 3 Establish local plants

## Metal-tolerant plants support recovery



### Indicator plants

Signal metal-rich ground.  
Useful in exploration.

### Excluder plants

Keep metals out of tissue.  
Help stabilise cover.

### Hyperaccumulators

Store metals in biomass.  
Can support phytomining.

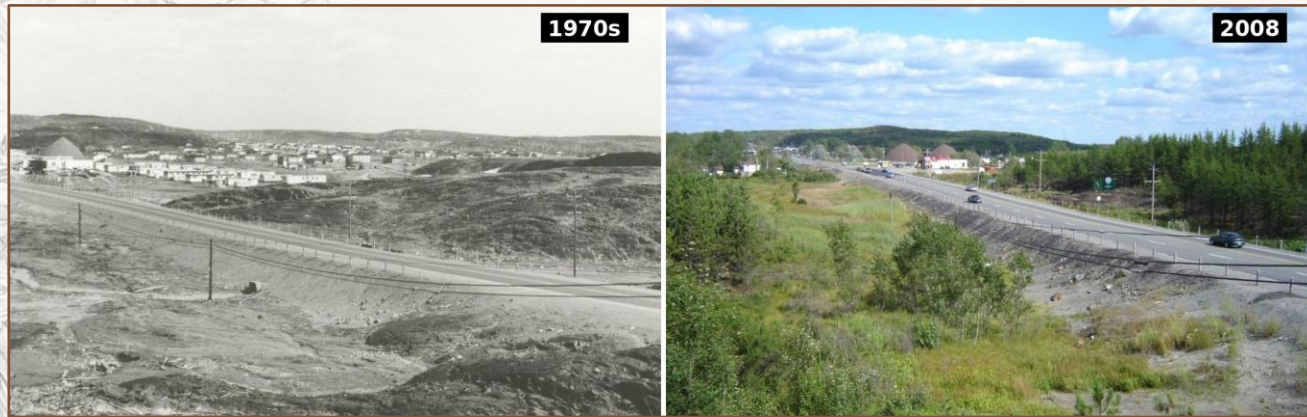
## Land use continues

Former mine sites can become forests, farms or lakes.

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Sudbury in Canada shows both how bad it can get and how much can be undone.



The same stretch of road near Sudbury, before and after regreening.

## The damage

A century of nickel and copper mining and smelting.  
Sulfur dioxide acidified soils across a wide area.  
Vegetation disappeared and erosion left bare rock.

## The recovery

Emissions were cut at the source first.  
Acid soils were limed, then grasses were seeded.  
Trees followed once the soil could support them.  
More than fifty years of work, and still going on.

## What Sudbury does and does not prove

Severely damaged land can be brought back, but slowly and at a cost. Preventing the damage remains far cheaper.

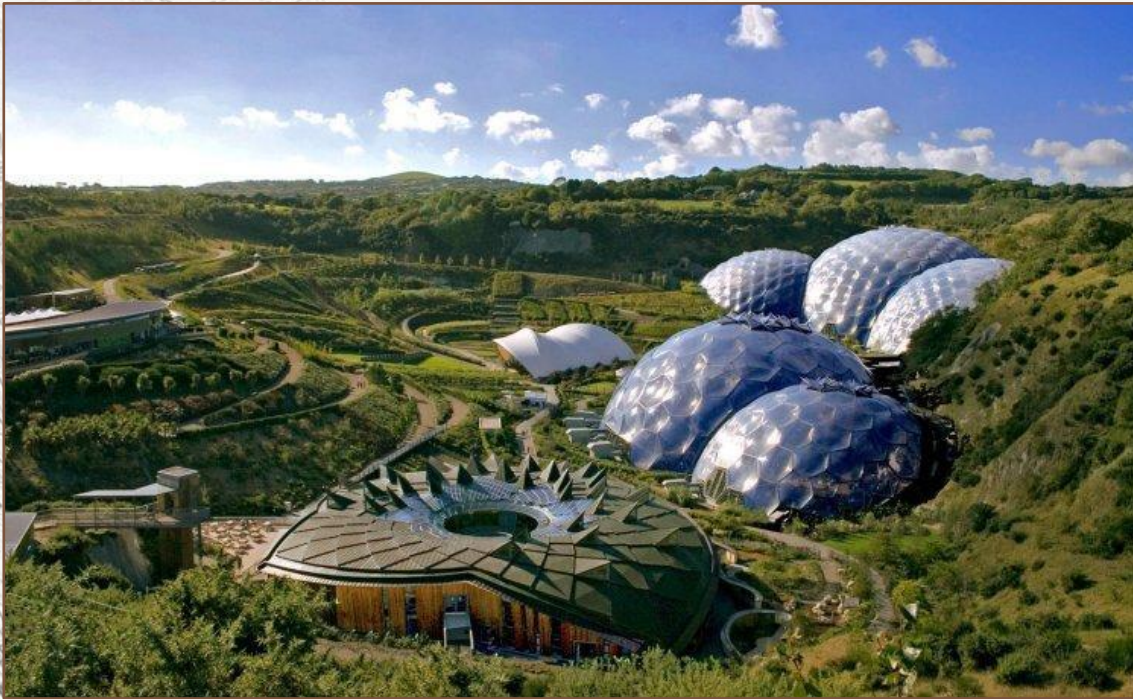
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# Eden Project: a clay pit becomes a garden

D: Resource

A worked out china clay pit in Cornwall now holds the largest greenhouses in the world.



Eden Project, Cornwall.

## What it was

A worked-out clay pit near St Austell: steep sides, no soil, no drainage.

## What it is now

Two linked biome domes with tropical and Mediterranean planting. The growing medium was manufactured on site from china clay waste and composted bark.

## Why it counts

About a million visitors a year. The pit earns more as a destination than it did as a pit, and the shape of the bowl is what made it work.

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Tailings were defined as waste by the technology and the prices of their time. Both change.

## Old processing was inefficient

Historic plants left part of the target metal behind.

## Some metals had no market

Rare earths, germanium and gallium were simply discarded.

## Two problems, one solution

Reprocessing earns revenue and removes acid generating material.

## Two examples

Peru:  $1.64 \text{ Mt} \times 2.81 \text{ g/t} \times 97\% = \text{about } 4.5 \text{ t of recovered gold.}$

Ergo, Johannesburg: reprocessing historic tailings also frees urban land.

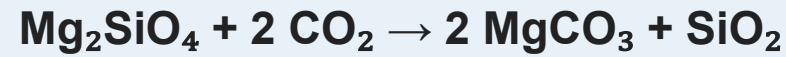
## The catch

Reprocessing produces new tailings of its own. It reduces a liability, it does not delete it.

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Mining causes roughly a tenth of global greenhouse gas emissions. Some of its waste can absorb carbon dioxide.



## What that is worth at one mine

A nickel operation produces 11 Mt of tailings a year. If a quarter is ultramafic and half of that reacts, it binds roughly 0.86 Mt of carbon dioxide a year.

Studied at Mount Keith in Australia and the Baptiste deposit in British Columbia.

## Keep the scale honest

Passive carbonation is slow and only works for genuinely ultramafic tailings.

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After Brumadinho the question stopped being technical. It became a question of accountability.

## A global standard

The Global Industry Standard on Tailings Management, 2020.

## A public inventory

Companies now publish their facilities. The database is still incomplete.

## Continuous monitoring

Satellite and drone imagery, radar, piezometers.

## Someone has to stay

A facility outlives the company that built it.

## The question this DTM leaves you with

Greenland holds deposits that Europe wants, in an environment where mistakes are slow to heal. Who decides what happens next, who benefits, and who carries the risk once the company is gone?

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# Key takeaways



Mining is one of the largest waste producers on Earth: about 25 Gt a year, and rising as ore grades fall.



Tailings are the biggest footprint and the biggest risk. Upstream dams are the cheapest to build and the most likely to fail.



Acid mine drainage is chemistry, not bad luck. It can be predicted before a mine opens, and prevented far more cheaply than it can be treated.



Closure begins on day one. A site is closed domain by domain, and rehabilitation takes decades.



Waste is a category, not a property. Yesterday's tailings can be today's ore, and some of them can even bind carbon dioxide.

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