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A Quick Introduction to Sulphidic Rock Drainage at Mine Sites

BVRC Seminar Series - October 9, 2019

Copper in near-neutral natural drainage

Iron in acidic mine drainage

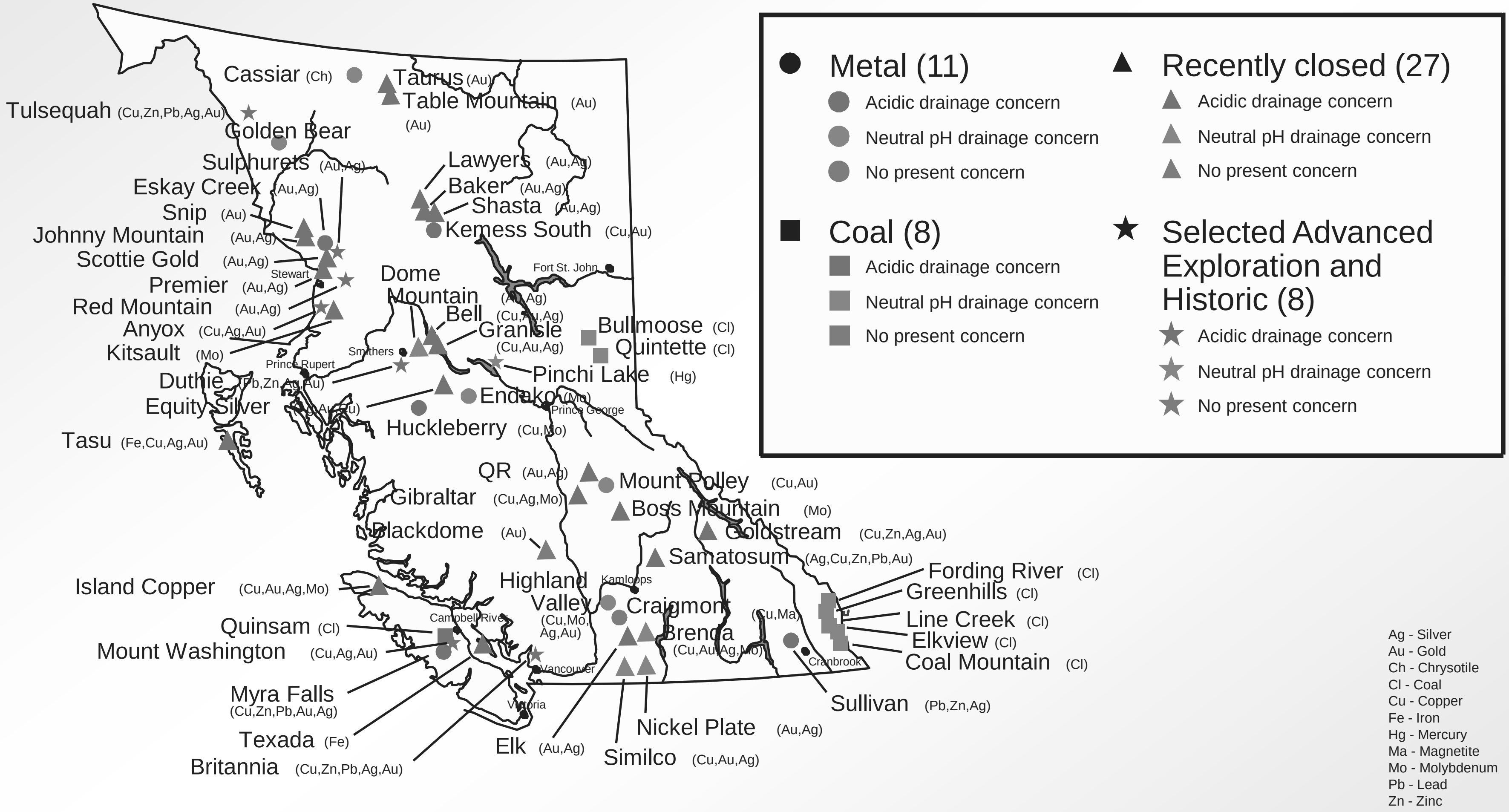
Topics covered will be:

1. **Why care and challenges**
2. **Properties and processes of sulphidic rock and how they affect drainage**
3. **Sulphide geologic materials**
4. **Mitigation tools and procedures**
5. **Conclusions**

Why Care and Challenges:

Requirements and challenges for prevention of impacts from sulphidic materials

Ensuring well informed, environmentally sound mining and management of closed mines is important both for jurisdictions with many mines and society in general. Operating mines are the tip of the ice berg. Most mines are closed and therefore most ML/ARD management issues are at closed sites.



OPERATING AND CLOSED MAJOR MINE SITES IN B.C in 2003.

Since this map was produced, BC has added many new mines with acidic or neutral pH concerns

You should care because food production, housing, energy production, health care and transportation all depend on products from mining sulphidic rock. This includes:

- coal and iron for steel in vehicles, machinery, construction etc…
- trace metals such as copper, lead and zinc for engines, wire and electronics
- precious metals such as gold and silver for electronics and safety devices
- coal and uranium for power
- diamonds for cutting and polishing.

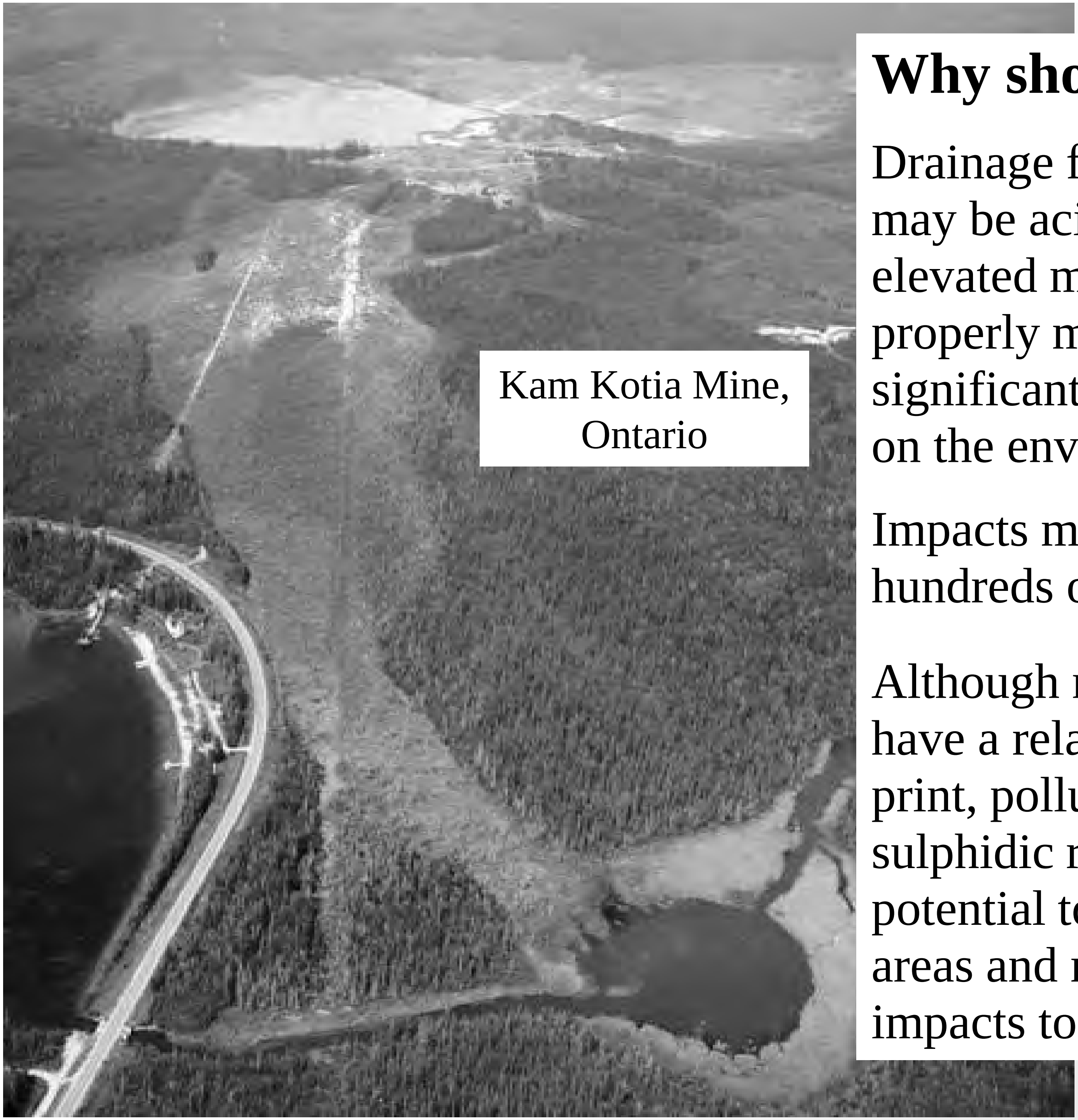
Huckleberry Copper Mine

People’s need for the products of sulphide mining mean that the question is not whether there will be sulphidic mining but whether society will manage sulphidic mines and mine sites responsibly.

This does not mean the public should accept poor mines and poor mining practices, but rather that they require good mining practices, reject poor proposals and practices, and develop a capacity for long-term management.

The costs of failure are prohibitively expensive.

Opposition to mine dumping mounts


Kam Kotia Mine, Ontario

Why should you care?

Drainage from sulphidic rock may be acidic or contain elevated metals which if not properly managed can have significant negative impacts on the environment.

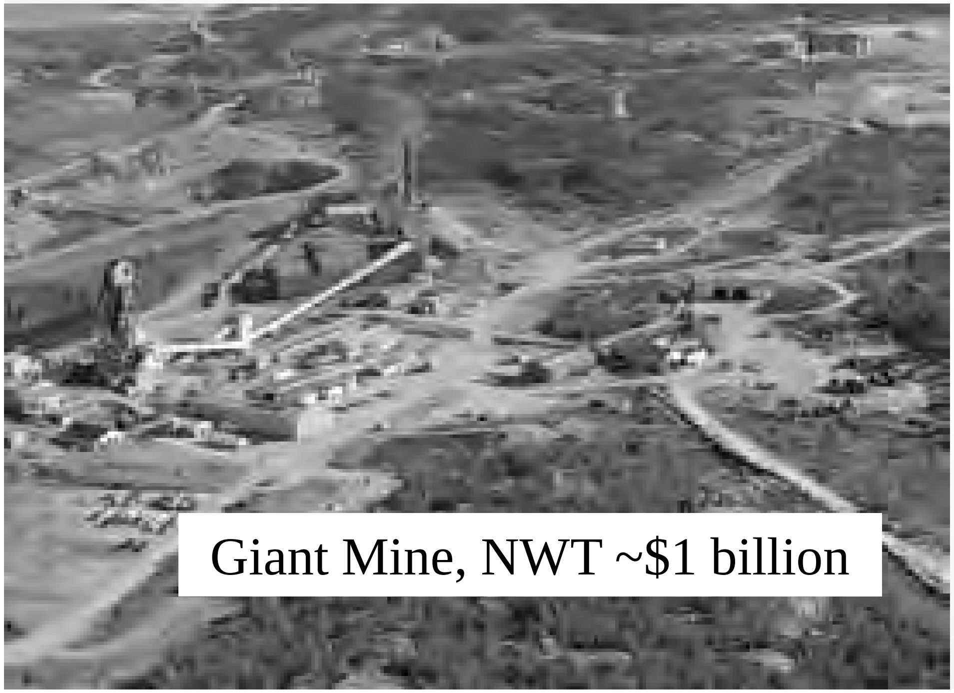
Impacts may persist for hundreds of years.

Although mines themselves have a relatively small foot print, polluted drainage from sulphidic rock has the potential to impact large areas and result in extensive impacts to aquatic resources.

Previous mining has had extensive downstream impacts and created large remediation costs.

Historic mining impacts 25% of the watersheds in the Western US.

Remediation costs for Canadians include ~$1 billion each for the Giant and Faro Mines and $100 million for the Britannia Mine.



Giant Mine, NWT ~$1 billion

Britannia Mine ~$100 million


Faro Mine, Yukon

Major challenges include:

- potentially high costs and large environmental impacts;
- need to be proactive;
- many contributing processes (large info. requirements);
- many key properties in flux and difficult to measure;
- mitigation must function over a long-time frame;
- limited long-term operating experience; and
- highly specialized, technical aspects of the work.

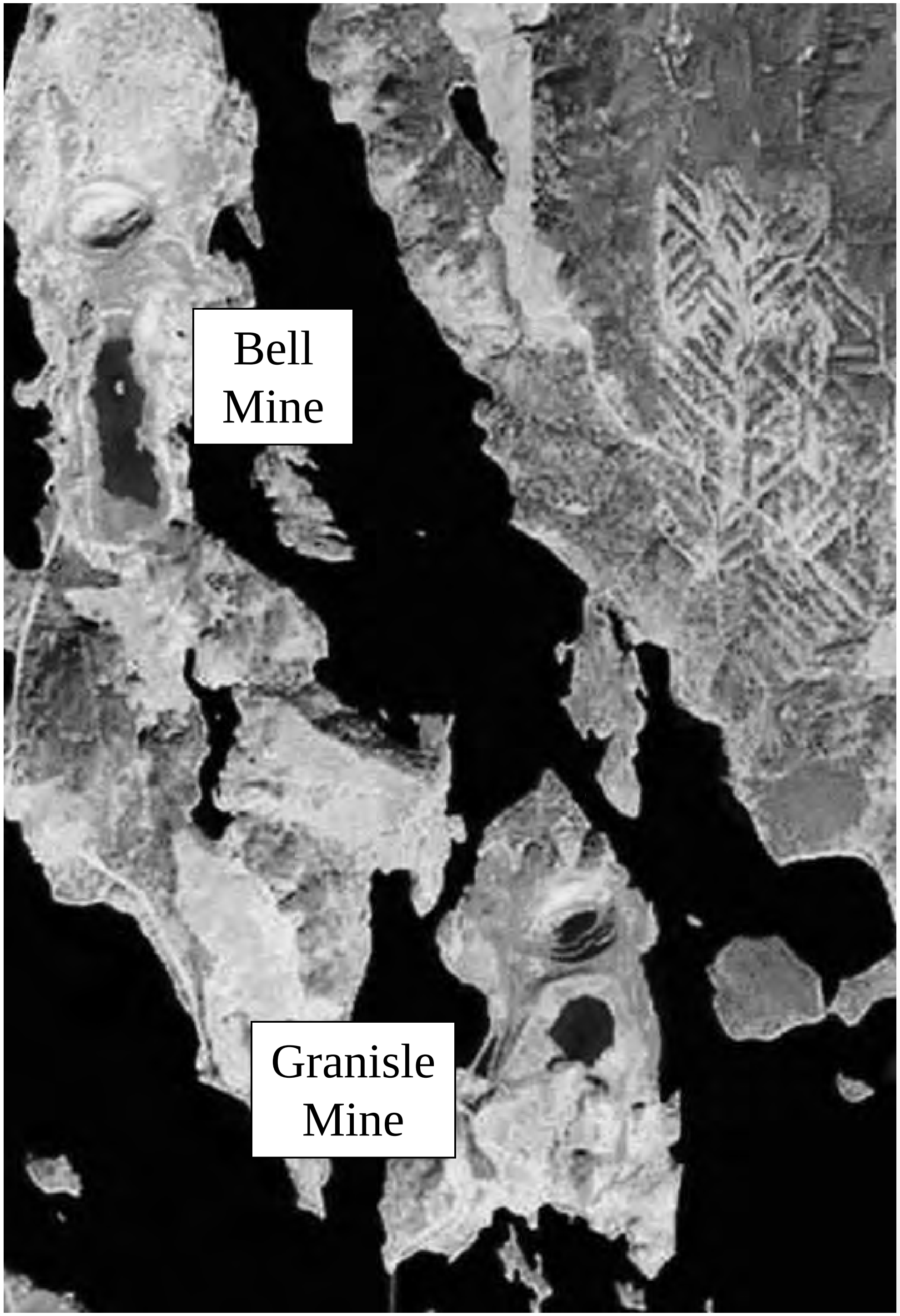
As a result, the risks and impacts and mitigation needs can play a major role in determining the economic feasibility, environmental risks and social support for a project.

Proactive

One key requirement and challenge is the need to be pro-active.

Mines must provide well-informed mitigation plans that demonstrate how issues will be proactively addressed, contaminant loadings will be reduced and receiving environment objectives achieved.

Impacts are minimized and mitigation measures are far more cost-effective if mitigation needs are incorporated into the initial mine plan.



Long-Term Maintenance

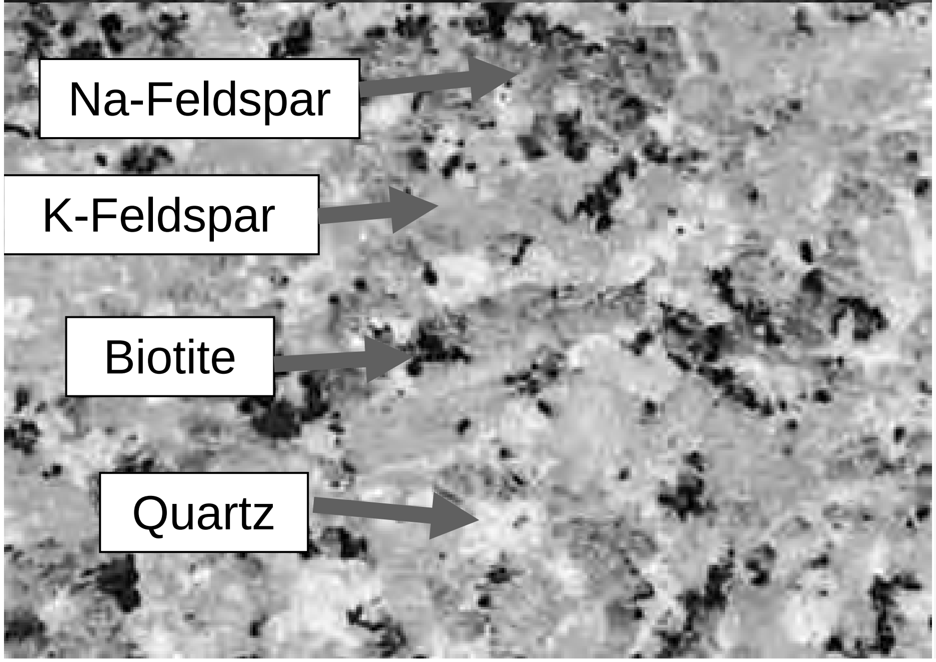
In order to function indefinitely, most mitigation measures require continual, long-term maintenance, monitoring, replacement, repair and a degree of adaptive management.

Where long-term operation and maintenance are required there is no walk-away and mitigation of sulphidic rock is a permanent, ongoing land use.

Success depends on attention to detail and a major challenge in the maintenance of mitigation measures is the lack of appetite and limited attention span of the public and government in dealing with the ongoing details.

Properties and processes of sulphidic rock and how they affect drainage

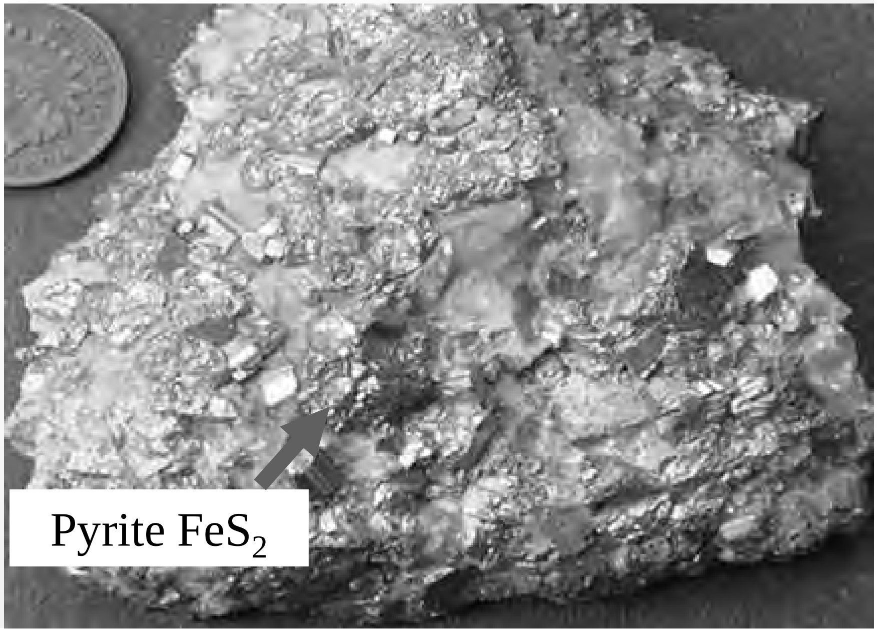
Geologic Materials



Geologic material are typically composed of sand or smaller sized mineral grains.

Minerals have a characteristic, elemental composition, distribution and structure.

Sulphide minerals contain a sulphide (S^{1-} or S^{2-}) with a metal or metalloid (e.g., Fe, Pb, As).

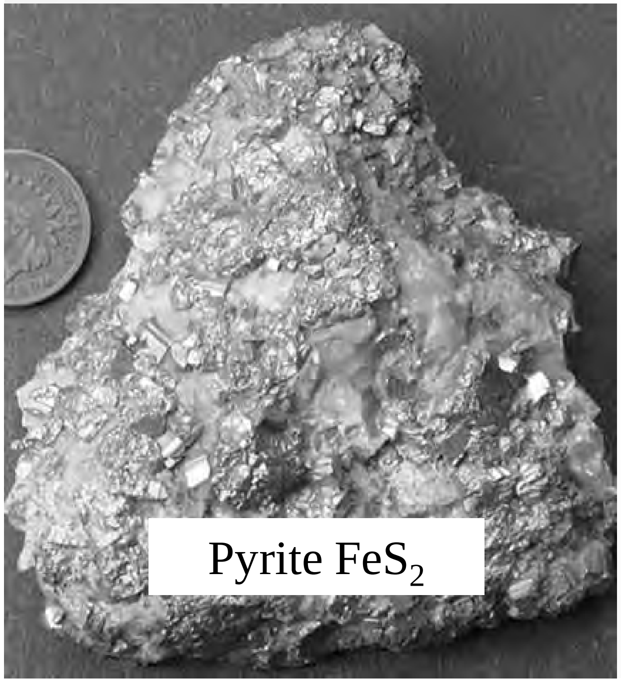


Sulphide Minerals

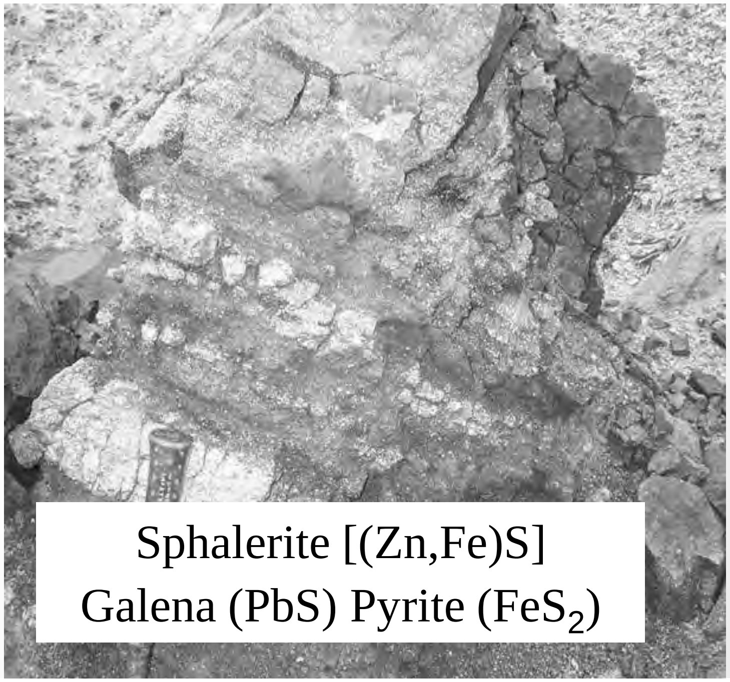
There are many types of sulphide minerals. The most common are Fe sulphides, especially pyrite (FeS_2).

Trace elements may be a small constituent in Fe sulphides or form a completely different mineral - Arsenopyrite (FeAsS), Chalcopyrite ($CuFeS_2$), Sphalerite [(Zn,Fe)S], Tetrahedrite $(Cu,Fe,Ag,Zn)_{12}Sb_4S_{13}$

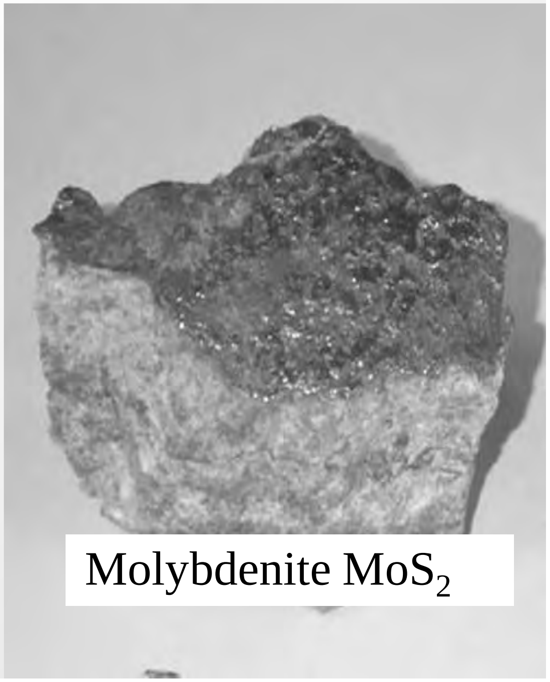
Most sulphide minerals are relatively insoluble, which is one reason why oxidation is so important.



Pyrite FeS_2



Sphalerite [(Zn,Fe)S]
Galena (PbS) Pyrite (FeS_2)



Molybdenite MoS_2

Weathering

Bedrock buried within the earth is physically and chemically stable.

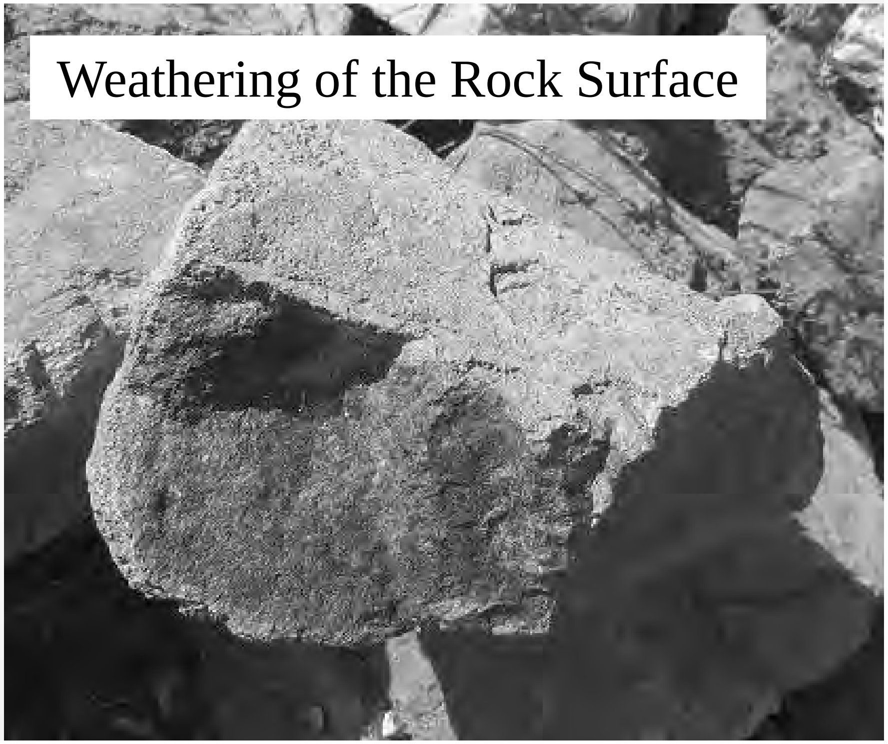
By creating walls and particles mining exposes rock surfaces to atmospheric phenomenon, such as air, water, freeze-thaw, wet-dry, biological activity and changes in temperature and pressure.

Rock exposed to atmospheric conditions is no longer stable and starts to physically and chemically change.

Alteration resulting from exposure to atmospheric conditions occurs at the surface and is called weathering.

There are a many different types of weathering reactions.

Unweathered Rock



Weathering of the Rock Surface

Fast Oxidation and Dissolution

All bedrock exposed to air and water is reactive, but reaction rates for most rock is very slow, and changes usually take thousands of years.

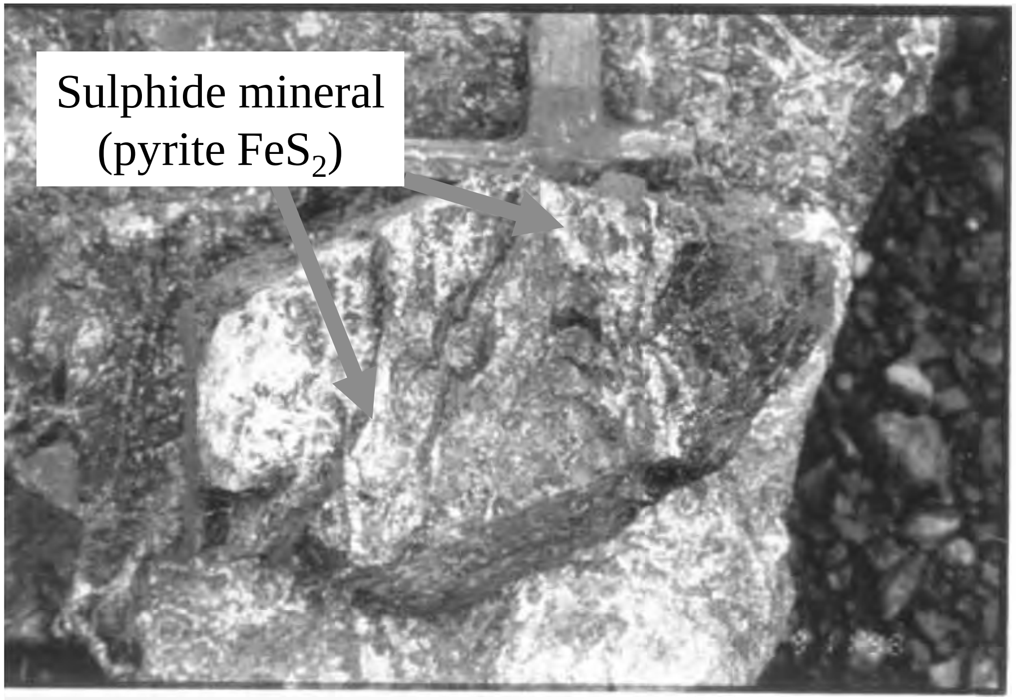
Rates of oxidation and dissolution of sulphide minerals and sulphidic rock exposed to air and water are relatively fast.

Fast rates of oxidation and dissolution are why drainage from exposed sulphidic rock may contain high concentrations of sulphate, metals and acid.

Drainage containing elevated metals and acid from sulphidic rock is often referred to as metal leaching and acid rock drainage (ML/ARD).

Kitsault Mine

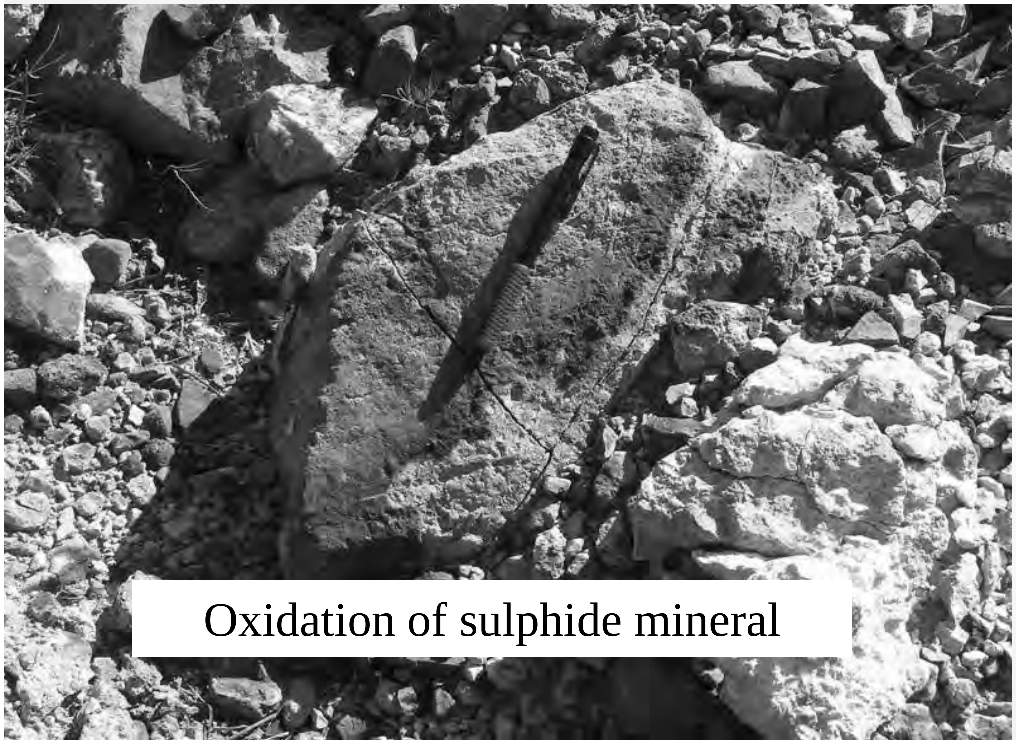
Occasionally sulphide oxidation is so fast that rock catches fire.



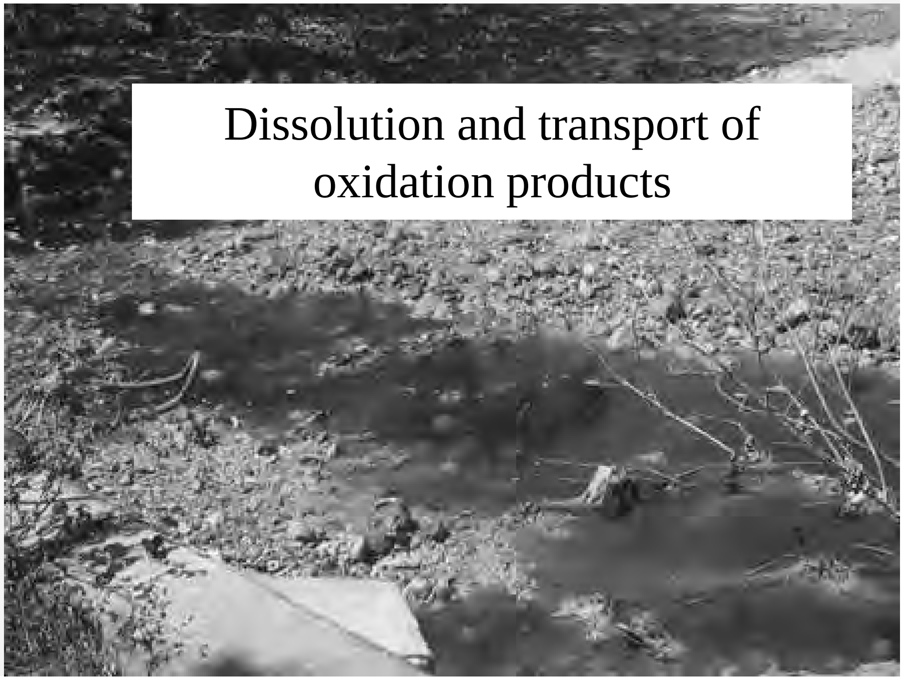
Sulphide mineral
(pyrite FeS_2)

The three weathering processes primarily responsible for the problems with drainage from sulphidic rock are:

- oxidation of sulphide minerals (loss of electrons or rusting) and then
- dissolution and transport of oxidation products by migrating water.



Oxidation of sulphide mineral



Dissolution and transport of oxidation products

Sulphide Oxidation

Sulphide minerals consist of sulphide (S^{1-} or S^{2-}) combined with metals (e.g., Pb) or metalloids (e.g., As).

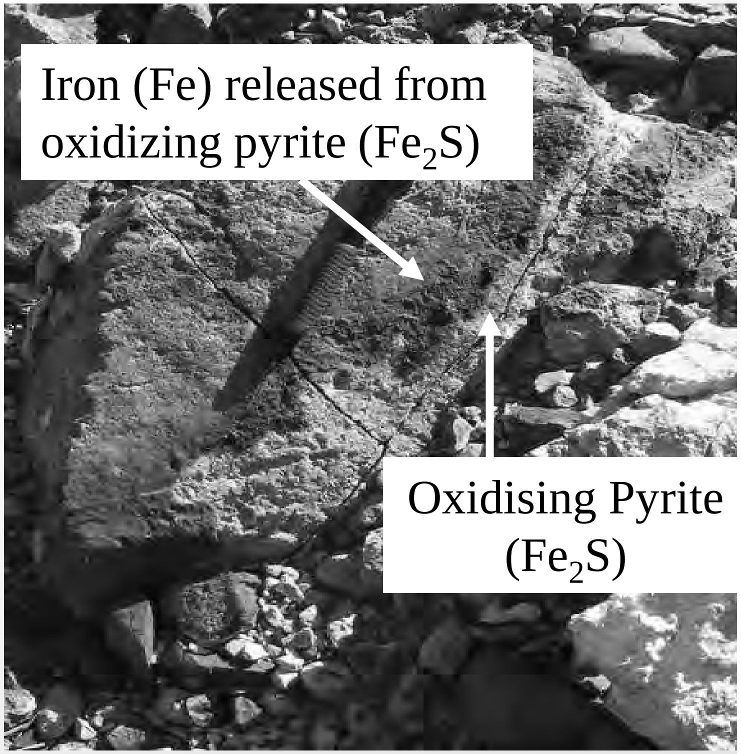
Oxidation transforms sulphide-sulphur (FeS_2-S) into sulphate (SO_4-S) and breaks the bond between the sulphur and metal ions (e.g., Fe or Zn).

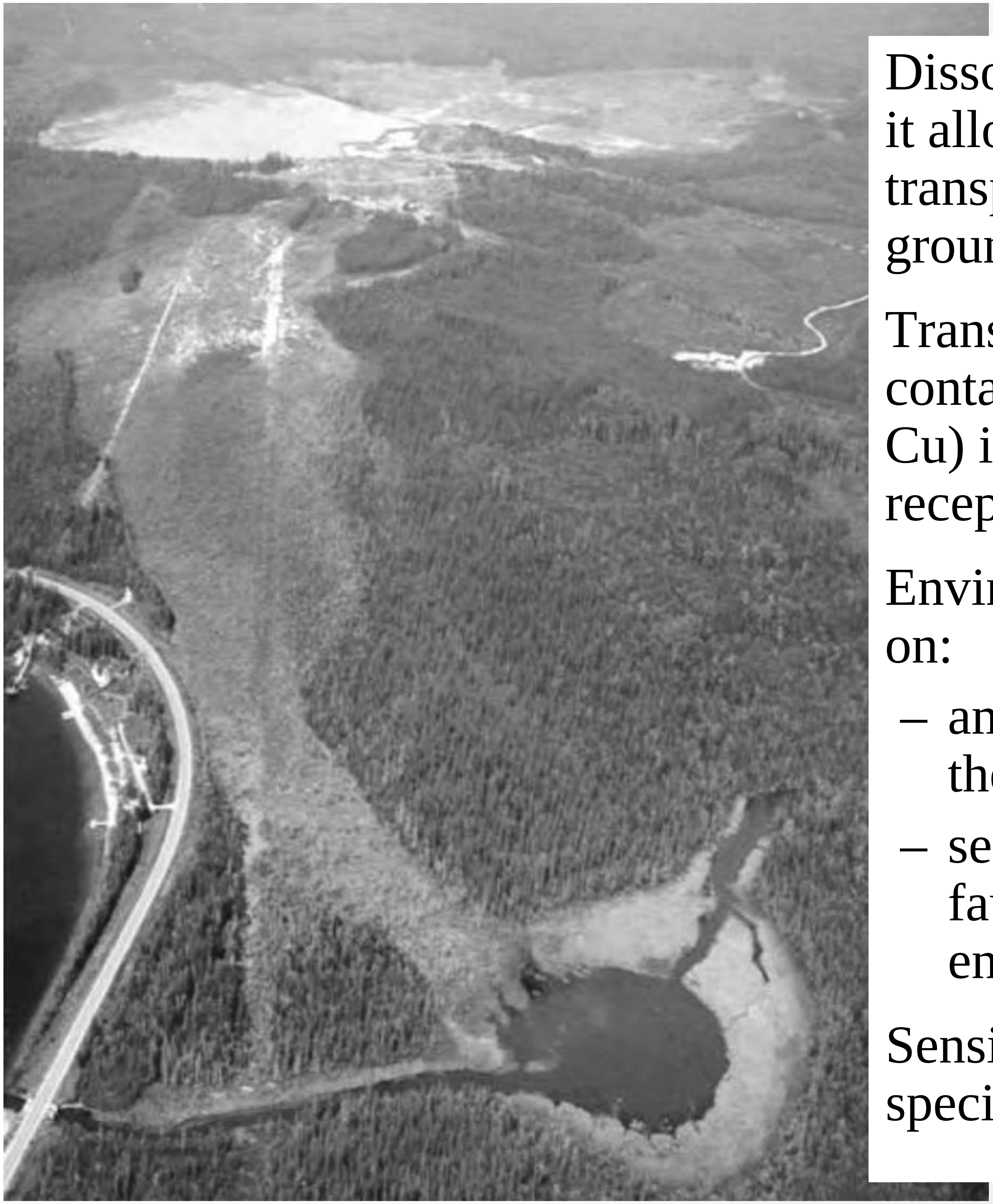
Oxidation is a critical part of the process because it can transform relatively insoluble components of sulphide minerals into chemical species that more easily dissolve.

Oxidation of sphalerite (ZnS) releases zinc (Zn):

$ZnS + 2O_2(aq) \rightarrow Zn^{2+}(aq) + SO_4^{2-}(aq)$

Note: (aq) indicates chemical species are dissolved.





Dissolution is important because it allows chemical species to be transported by surface and ground water.

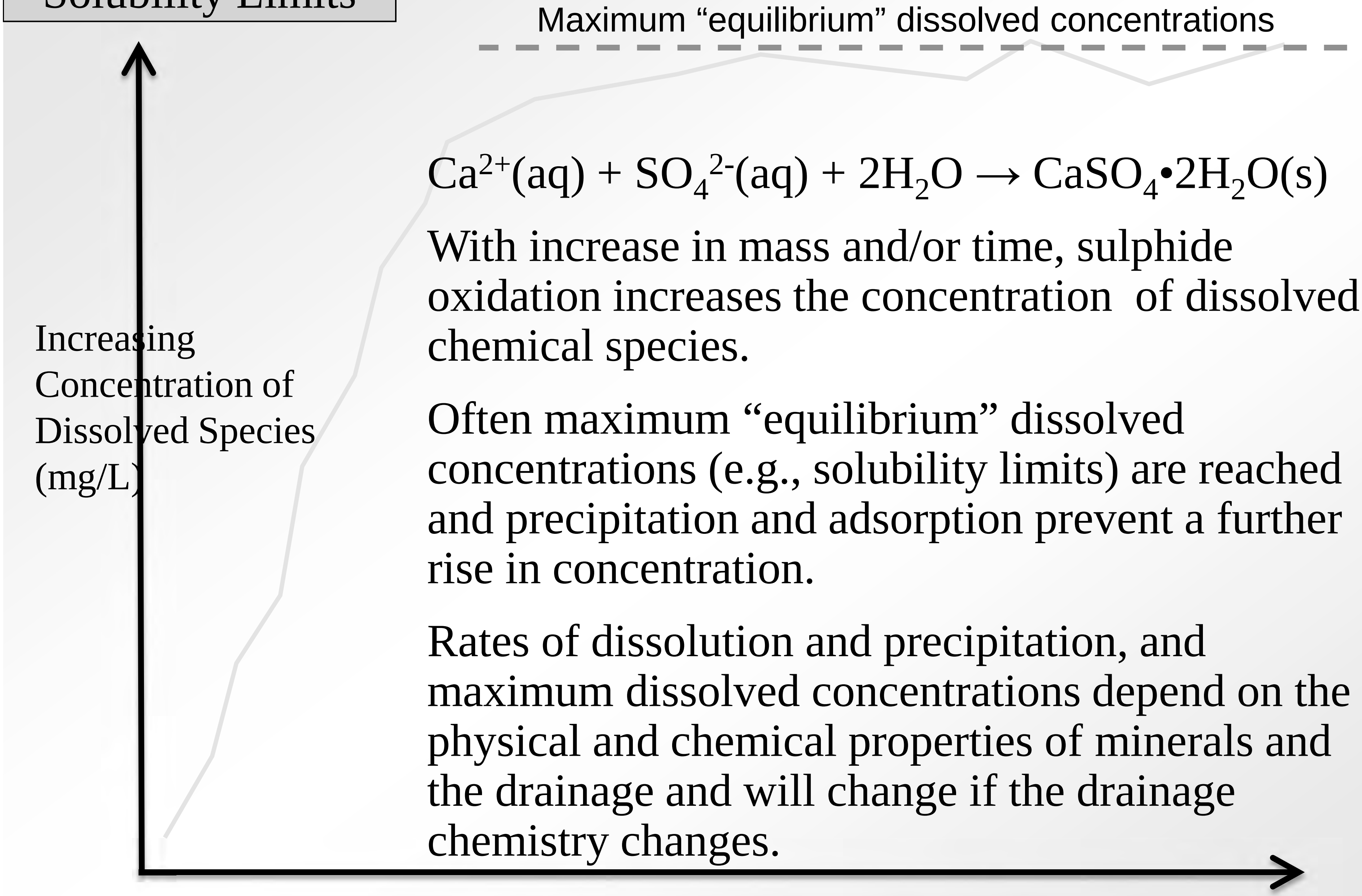
Transportation brings contaminants of concern (e.g., Cu) in contact with sensitive receptors (e.g., vegetation, fish).

Environmental impacts depend on:

- amount of contaminants in the drainage and
- sensitivity of the flora and fauna in the receiving environment.

Sensitivity varies with the species and the contaminant.

Solubility Limits



Maximum “equilibrium” dissolved concentrations

Increasing Concentration of Dissolved Species (mg/L)

$Ca^{2+}(aq) + SO_4^{2-}(aq) + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O(s)$

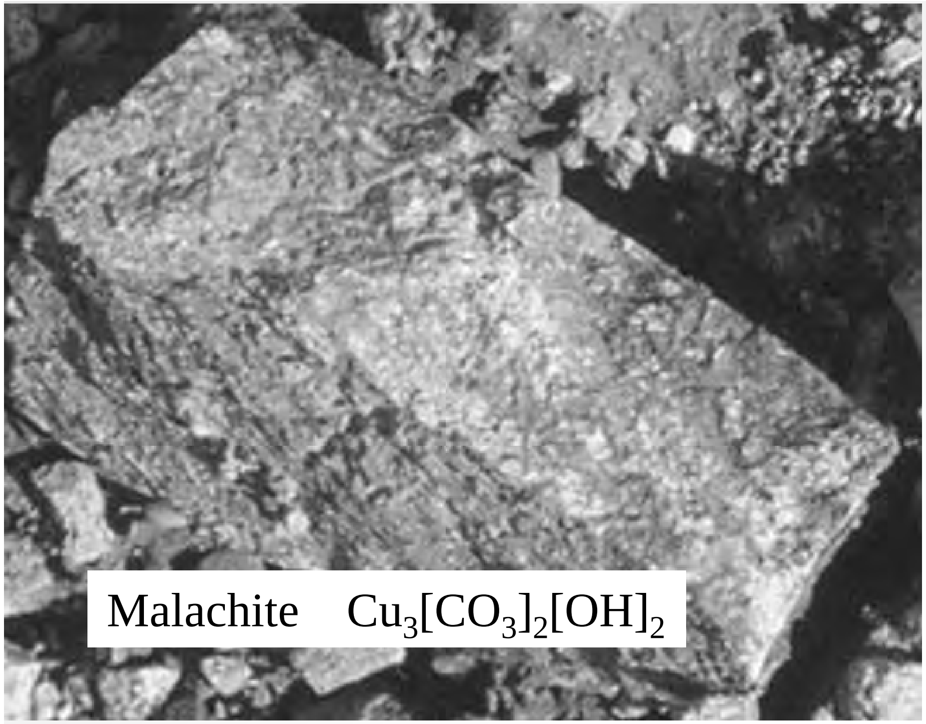
With increase in mass and/or time, sulphide oxidation increases the concentration of dissolved chemical species.

Often maximum “equilibrium” dissolved concentrations (e.g., solubility limits) are reached and precipitation and adsorption prevent a further rise in concentration.

Rates of dissolution and precipitation, and maximum dissolved concentrations depend on the physical and chemical properties of minerals and the drainage and will change if the drainage chemistry changes.

Increasing Rock Weight or Volume, Solid:Liquid Ratio, Reaction Rate or Time

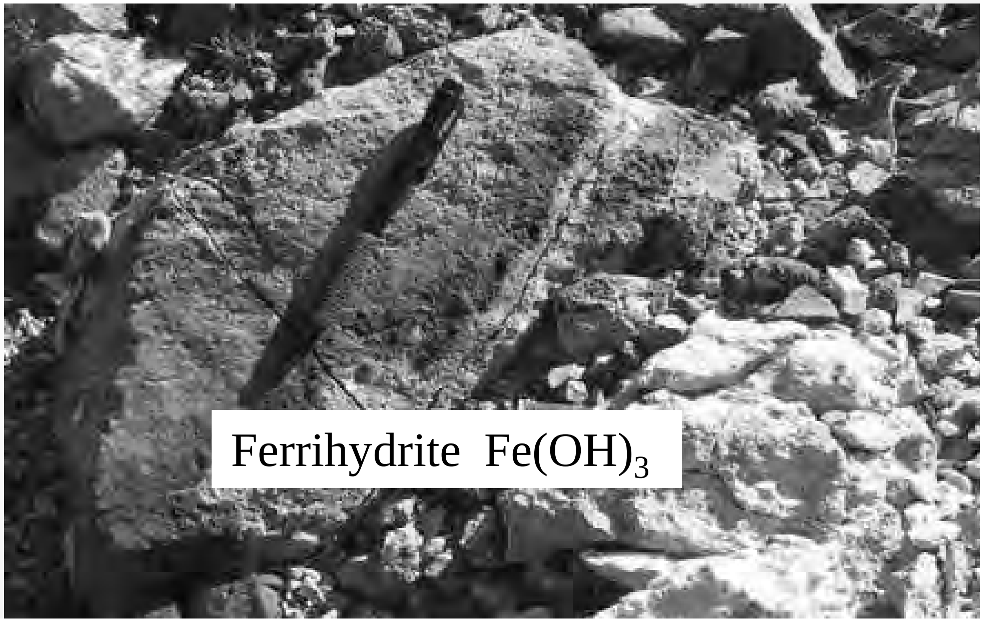
Morin, K.A., and N.M. Hutt. 2007. Scaling and Equilibrium Concentrations in Minesite-Drainage Chemistry. MDAG Internet Case Study #26, www.mdag.com/case_studies/cs26.html



Malachite $Cu_3[CO_3]_2[OH]_2$

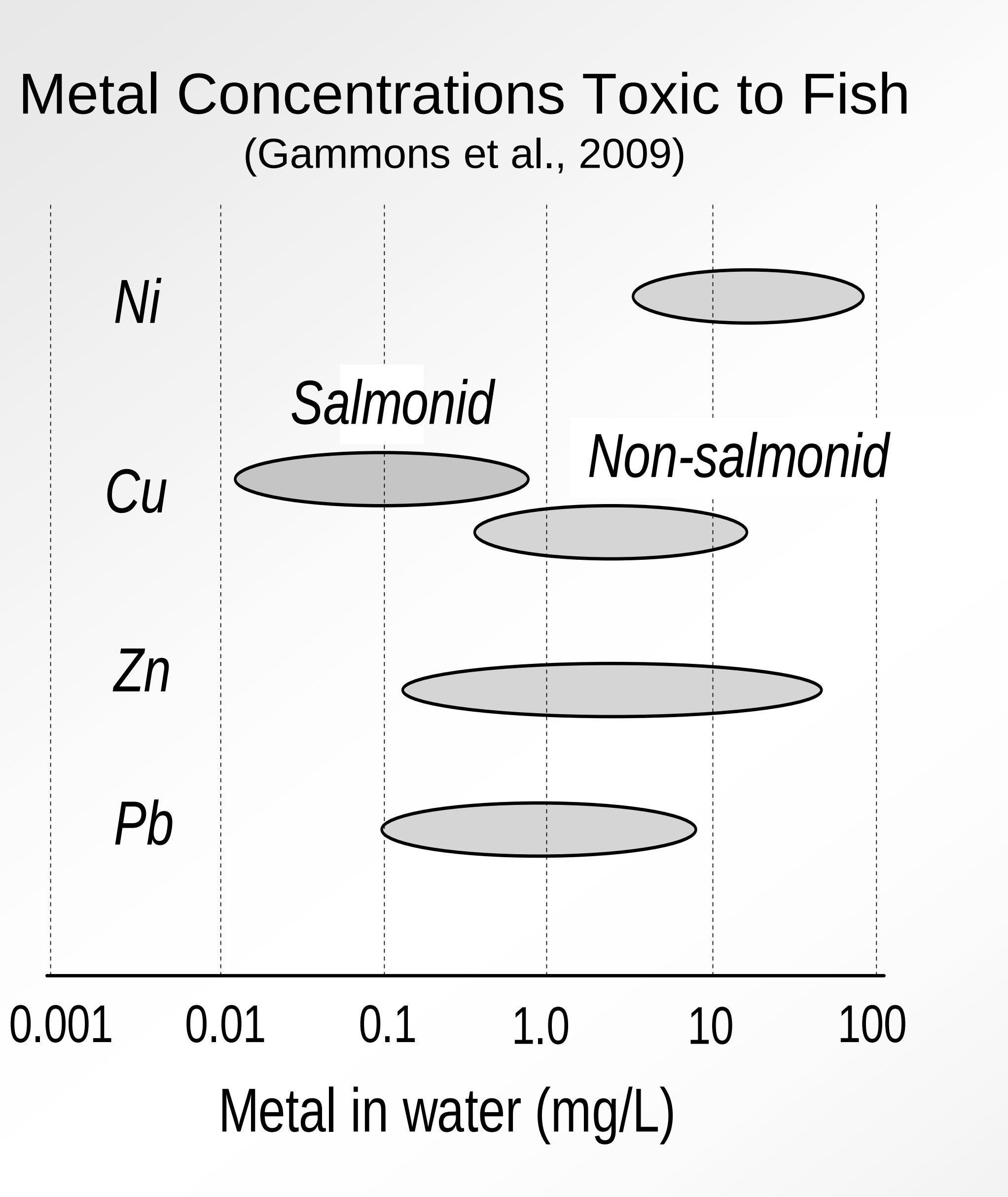
Dissolved oxidation products may reach solubility limits and precipitate in-situ or downstream.

Knowledge of site-specific, maximum dissolved metal concentrations and conditions that lead to mineral precipitation are very valuable when predicting drainage chemistry and possible environmental impacts.



Ferrihydrite $Fe(OH)_3$

Metal Leaching



The term ‘metal leaching (ML)’ is used because high concentrations of dissolved major metals (Fe and Al) and especially trace metals (e.g., Pb, Ni, Cu and Zn) are the most common environmental problem resulting from sulphidic rock.

Environmental impacts may also occur due to high concentrations of metalloids (arsenic and antimony) and non-metals (selenium and sulphate).

Note, just as all rock is reactive but most react slowly, all rock releases metals but usually at a much slower rate than sulphidic rock.

Toxicity

Some of the elements, such as copper, zinc and selenium, in sulphide minerals are nutrients and essential for healthy growth.

Natural water bodies already contain all the metals and other elements released by sulphide oxidation.

Harmful effects from ML/ARD primarily result from dissolved concentrations (e.g., mg/L) of existing elements becoming too high.

Speciation of dissolved elements may play a role. Complex formation with OH^-, CO_3^{2-}, HCO_3^- and CH_3 can reduced metal toxicity (e.g., Cu-COOH, $ZnCO_3^o$). An exception is methylated mercury (CH_3Hg).

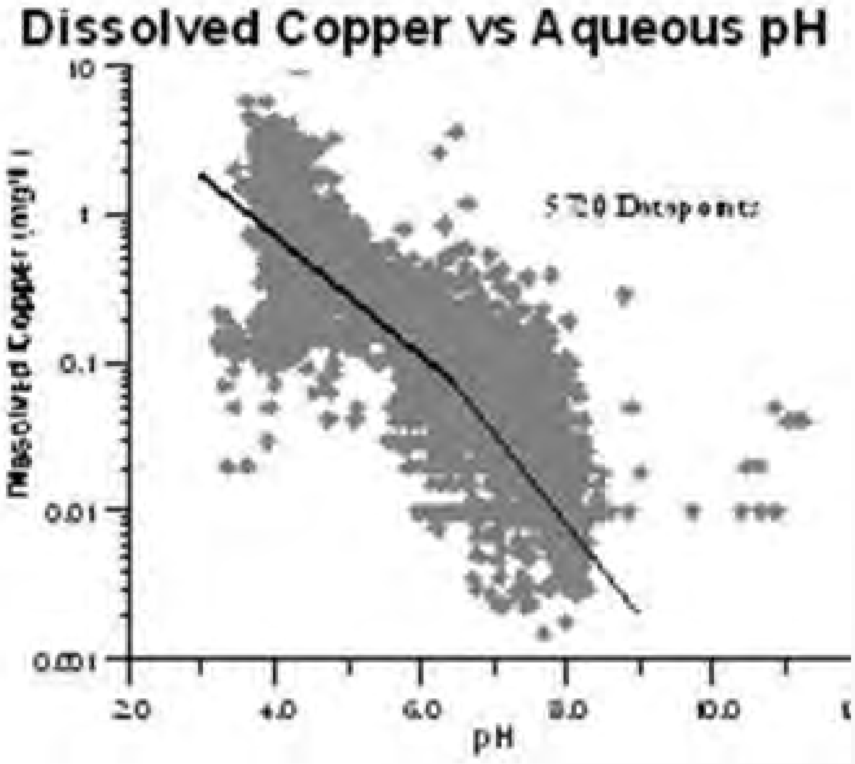
Change in oxidation state may also alter toxicity (e.g., As^{3+} more toxic than As^{5+}).

Acidic Rock Drainage (ARD)

In addition to metals, sulphide oxidation produces acid and can result in drainage with an acidic pH.

Pyrite: $FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$

Environmental impacts are greater and more common when the drainage pH is acidic for two reasons.



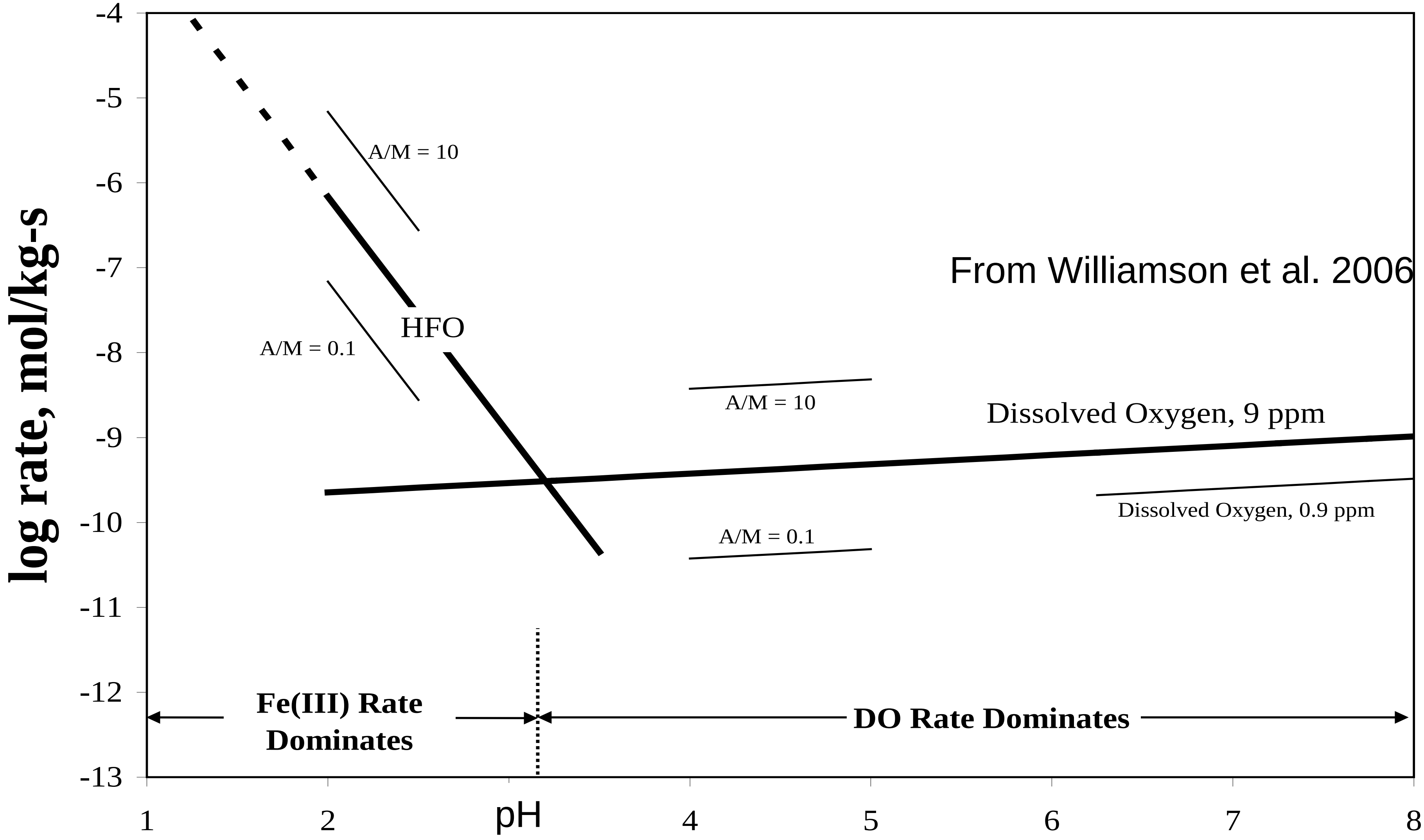
Source: Morin and Hutt, 1997

First, an acidic pH increases the solubility and the maximum “equilibrium” dissolved concentrations of most metals.

Increased metal solubility is illustrated by the increased copper concentrations as the pH decreases at Island Copper.

An exception is the metal molybdenum whose solubility decreases at an acidic pH.

The <u>second</u> reason environmental impacts are more common when the drainage pH is acidic is because the rate of sulphide oxidation increases below pH 3.5. An increase in the rate of sulphide oxidation increases the rate of release of both acid and potentially problematic elements.



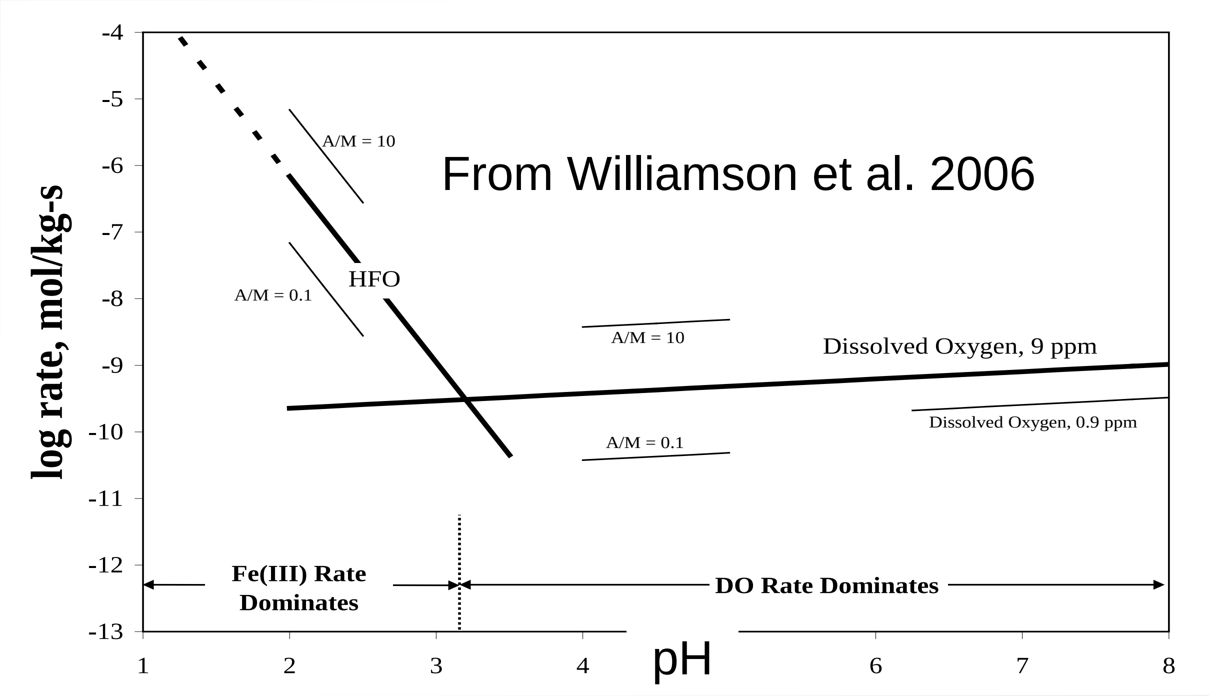
From Williamson et al. 2006

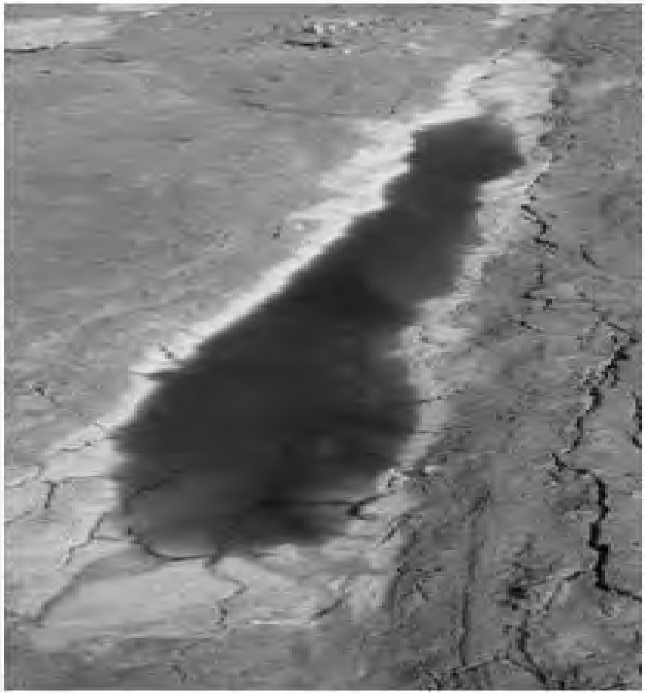
Sulphide oxidation occurs in a film of water on the mineral surface and therefore sulphide oxidizing agent must be dissolved.

The primary oxidizing agents are dissolved oxygen (O_2) and iron (III - Fe^{3+}).

Above pH 3.5, the solubility and therefore the concentration of dissolved Fe(III) is low and the primary oxidizing agent is oxygen.

Below pH 3.5, dissolved Fe(III) concentrations are generally much higher than dissolved O_2 and rates of sulphide oxidation are much higher than at higher pH.

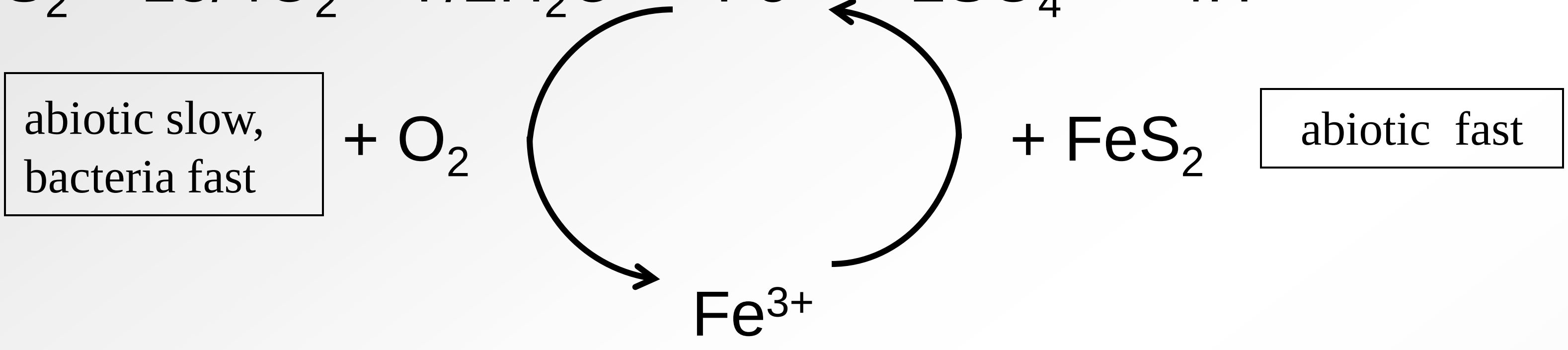

From Williamson et al. 2006



Role of Bacteria

Sulphide oxidation below pH 3.5

$$FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 4H^+$$



Sulphide oxidation by oxygen and Fe(III) occurs at a similar rate either abiotically or biotically.

The rate of abiotic oxidation of iron(II) to (III) is relatively slow and the mechanism by which bacteria increase the rate of sulphide oxidation is by increasing the rate of regeneration of Fe(III) from Fe(II). By increasing the resupply of Fe(III), iron oxidizing bacteria (e.g., Acidithiobacillus ferrooxidans) can accelerate sulphide oxidation by many orders of magnitude relative to abiotic rates.

Microbial activity does not accelerate sulphide oxidation at near-neutral or basic pH because Fe (III) is not soluble and therefore not an oxidizing agent.

Neutralization of ARD

Not all oxidizing sulphidic rock is acidic.

Drainage pH depends on the relative reaction rates of:

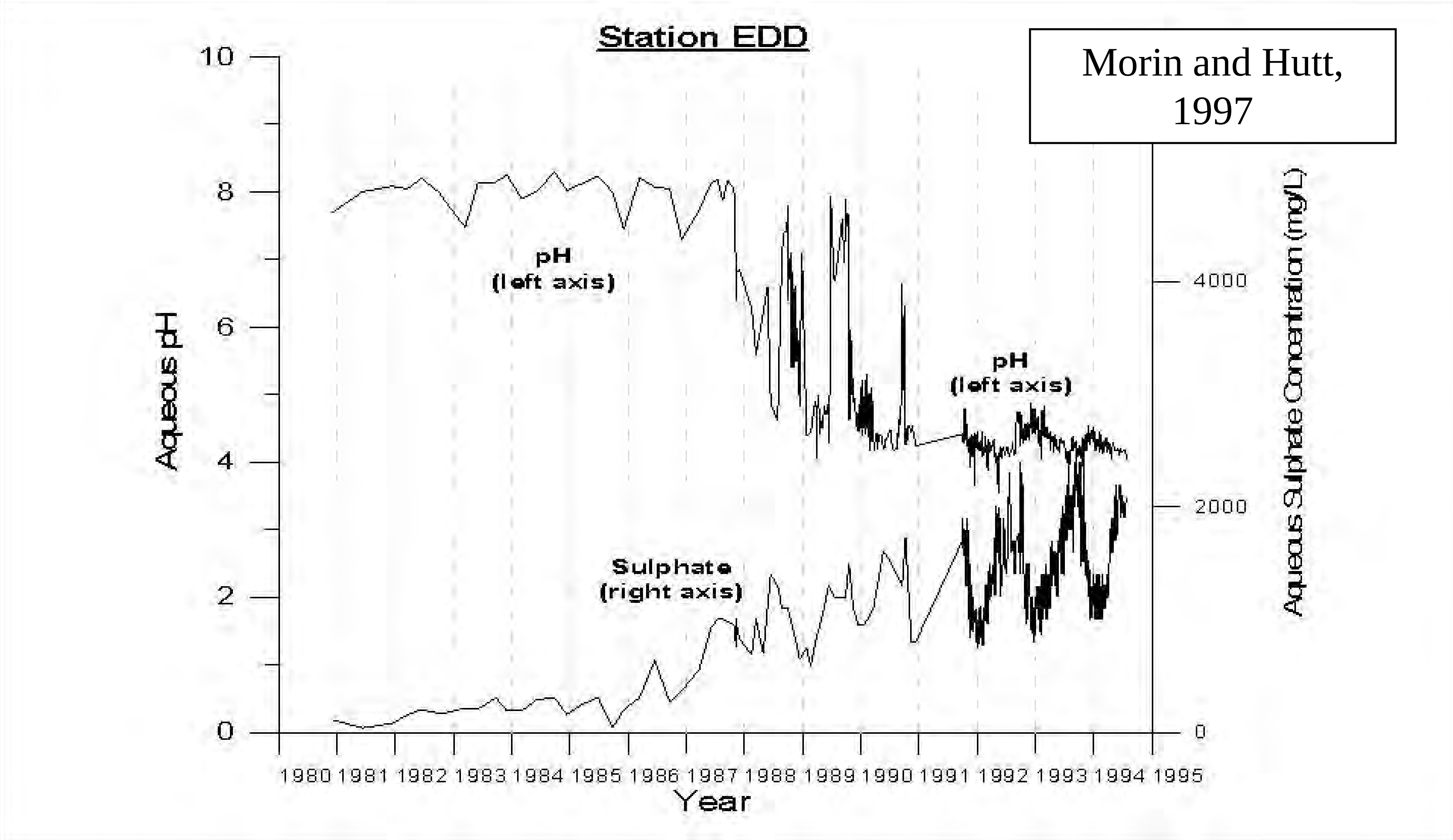
- acid generation by sulphur minerals and
- neutralization by other minerals (NP).

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + H_2O + CO_2$$

Acidic drainage will only result if the reaction rate of neutralizing minerals is too slow or neutralizing minerals are exhausted.

Calcium and magnesium carbonate minerals, such as calcite ($CaCO_3$), provide fast neutralization capable of matching the fastest rates of acid generation and are the primary source of neutralization.

It may take 10s to 100s of years before the depletion of neutralizing minerals results in acidic drainage. An absence of acidic drainage up to now does not prove it will not occur in the future. It took more than 15 years before acidic drainage was observed at Island Copper (see below).



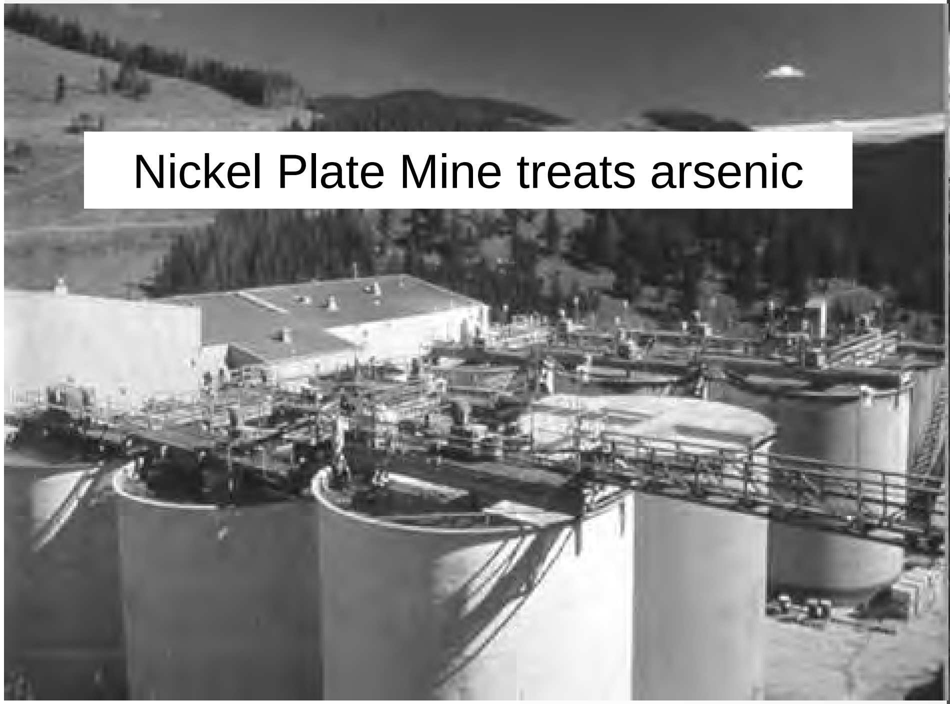
Morin and Hutt, 1997

Neutral and Basic pH Drainage may be a Concern

Dissolved trace element concentrations in drainage from sulphidic rock are usually lower at near-neutral or basic pH than acidic pH, but may still exceed receiving environmental guidelines (Stantec, 2004).

Element	pH	Example of Dissolved Concentration (mg/L)	Most Restrictive Receiving Environment Guideline (mg/L)
Antimony	8.5	0.9	0.006
Arsenic	8.0	0.3	0.005
Cadmium	6.5	0.07	0.000017
Cobalt	8.0	1.1	0.0009
Copper	7.3	0.06	0.002
Manganese	8.1	33.5	0.05
Molybdenum	8.3	29	0.073
Nickel	8.1	3.8	0.025
Selenium	7.5	1.6	0.001
Zinc	8.1	14.4	0.03

Two of the most costly mitigation programs for sulphidic drainage at British Columbia mines treat near-neutral pH drainage: elevated molybdenum (Mo) at Brenda near Peachland and arsenic (As) at Nickel Plate near Hedley.



Nickel Plate Mine treats arsenic

Brenda Mine treats molybdenum

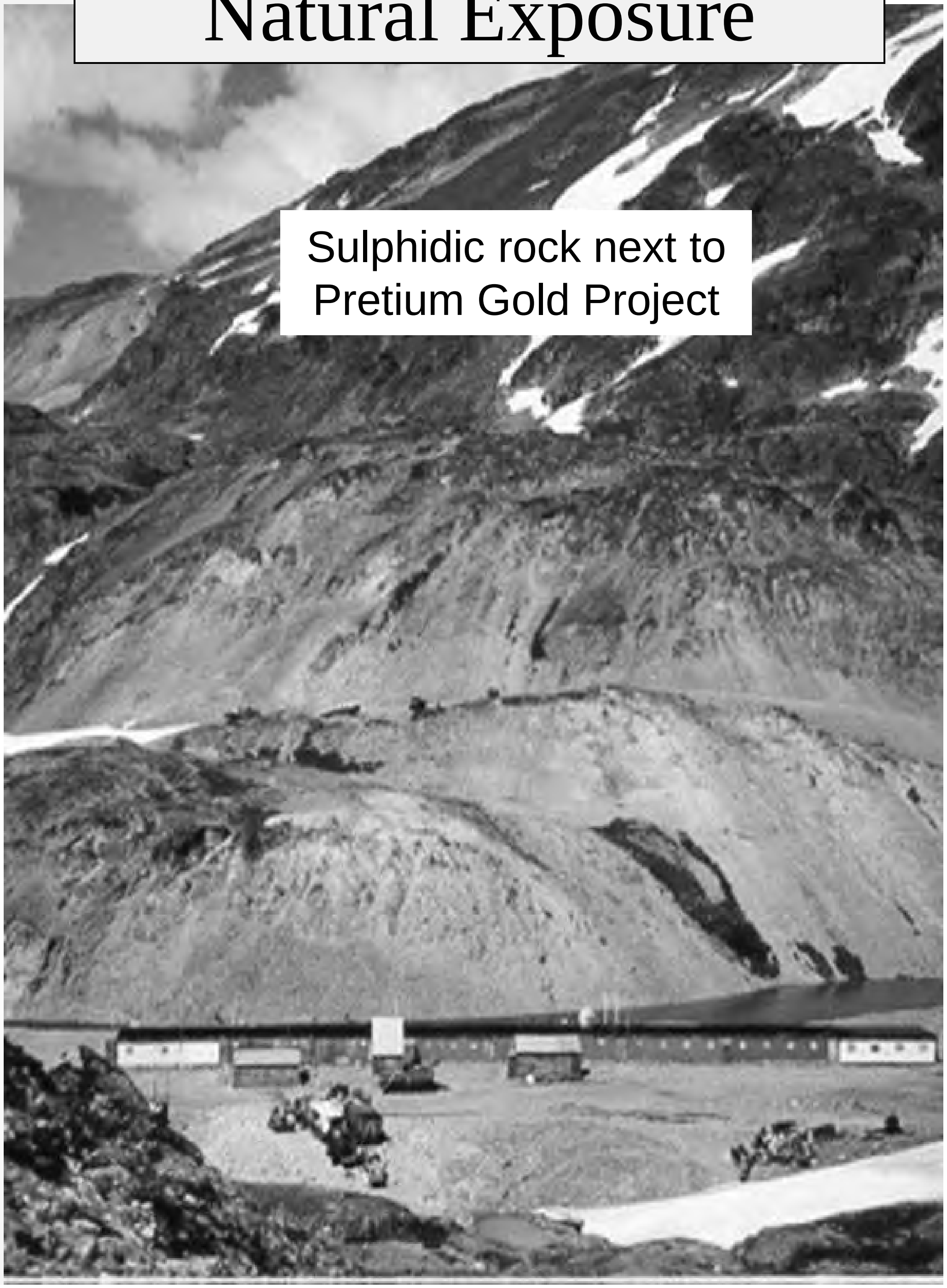
Sulphide Geologic Materials

Natural Exposure

Many activities expose sulphidic geologic materials to oxidation and leaching, not only mining.

Natural sulphidic outcrops and talus produce elevated metal leaching and acidic drainage, but contaminant release is typically limited by the shallow depth and the slow rate of rock exposure.

High background concentrations of contaminants due to natural sulphidic outcrops and talus reduce the diluting, absorptive and attenuating capacity of the receiving environment and increase the cumulative effects of anthropogenic sources.

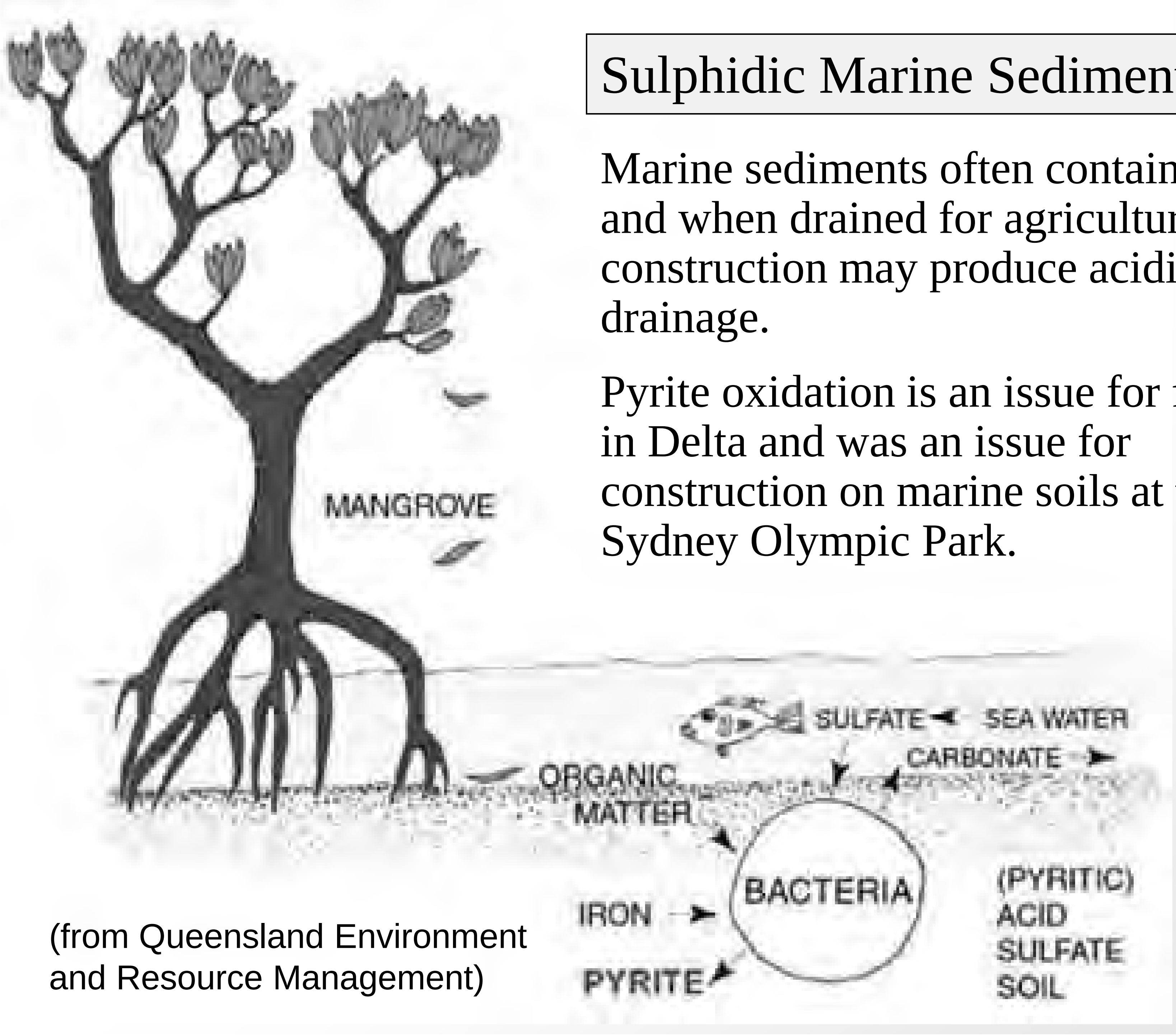


Sulphidic rock next to Pretium Gold Project

Sulphidic Marine Sediments

Marine sediments often contain pyrite and when drained for agriculture or construction may produce acidic drainage.

Pyrite oxidation is an issue for farmers in Delta and was an issue for construction on marine soils at the Sydney Olympic Park.



(from Queensland Environment and Resource Management)

Construction Projects

Construction projects expose large masses of rock to air and water.

Although most rock is not a concern, there are numerous examples where the rock is sulphidic and excavation and placement of materials in construction projects created environmental problems.

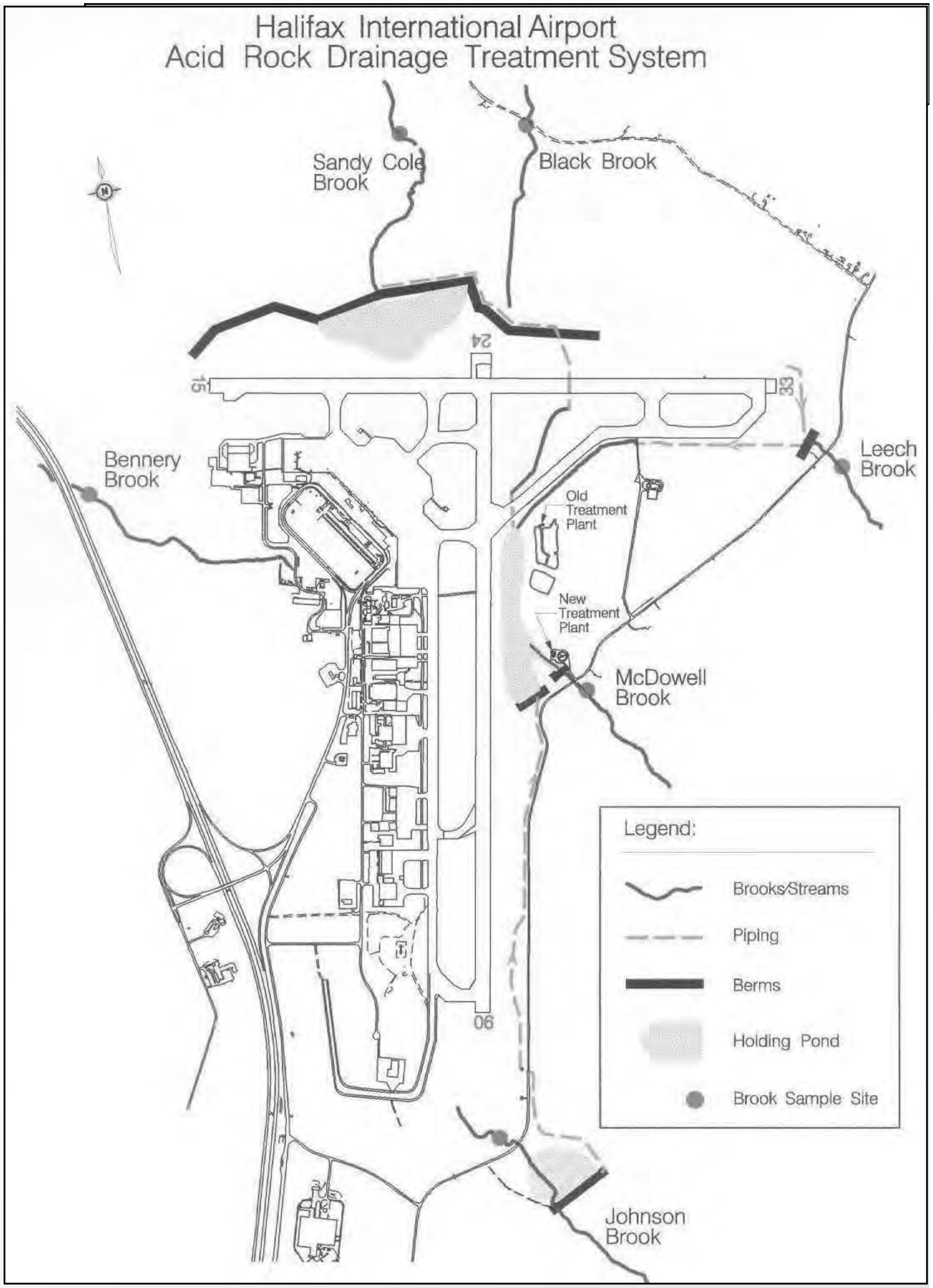
The adjacent pictures shows a section on the Coquihalla Connector highway in British Columbia where the cut and fill of sulphidic rock resulted in exposure of sulphidic rock and the discharge of acidic drainage into a stream upstream of a provincial trout hatchery.

Coquihalla Highway Cut

Coquihalla Highway Fill

Other examples of problems arising from construction in sulphidic rock are the problems created by various construction projects around Halifax, Nova Scotia.

Halifax airport must operate a lime treatment plant to treat its drainage (Hicks 2003).



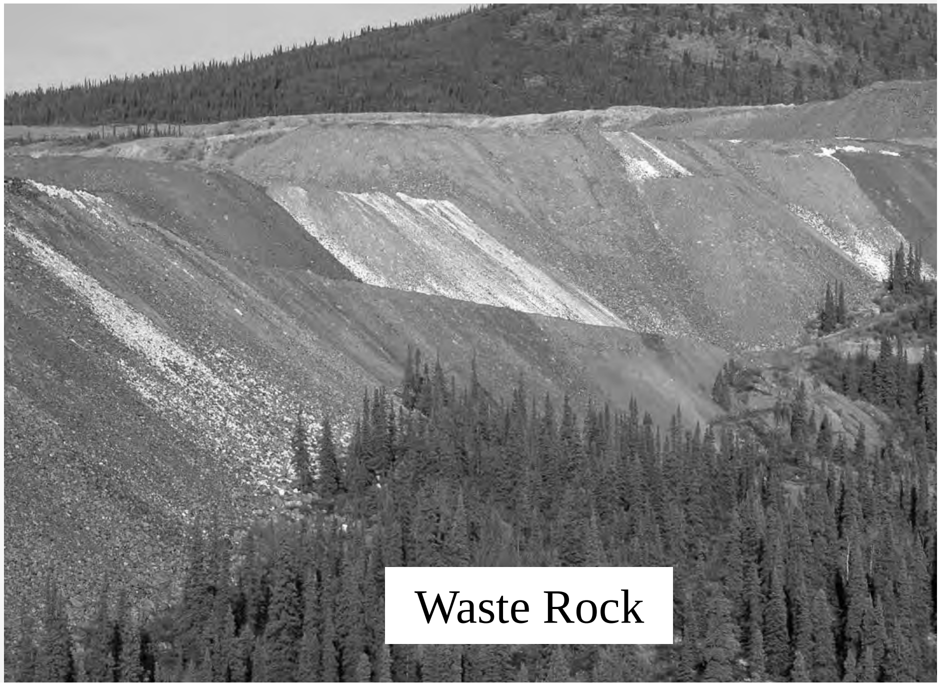
Mining


Open Pit

Sulphidic rock drainage is an important issue for mining because:

- mines rapidly excavate many billions of tonnes of rock
- rock at most precious and base metal, coal, diamond and uranium and some iron ore mines contain elevated concentrations of sulphide minerals.


Tailings


Waste Rock

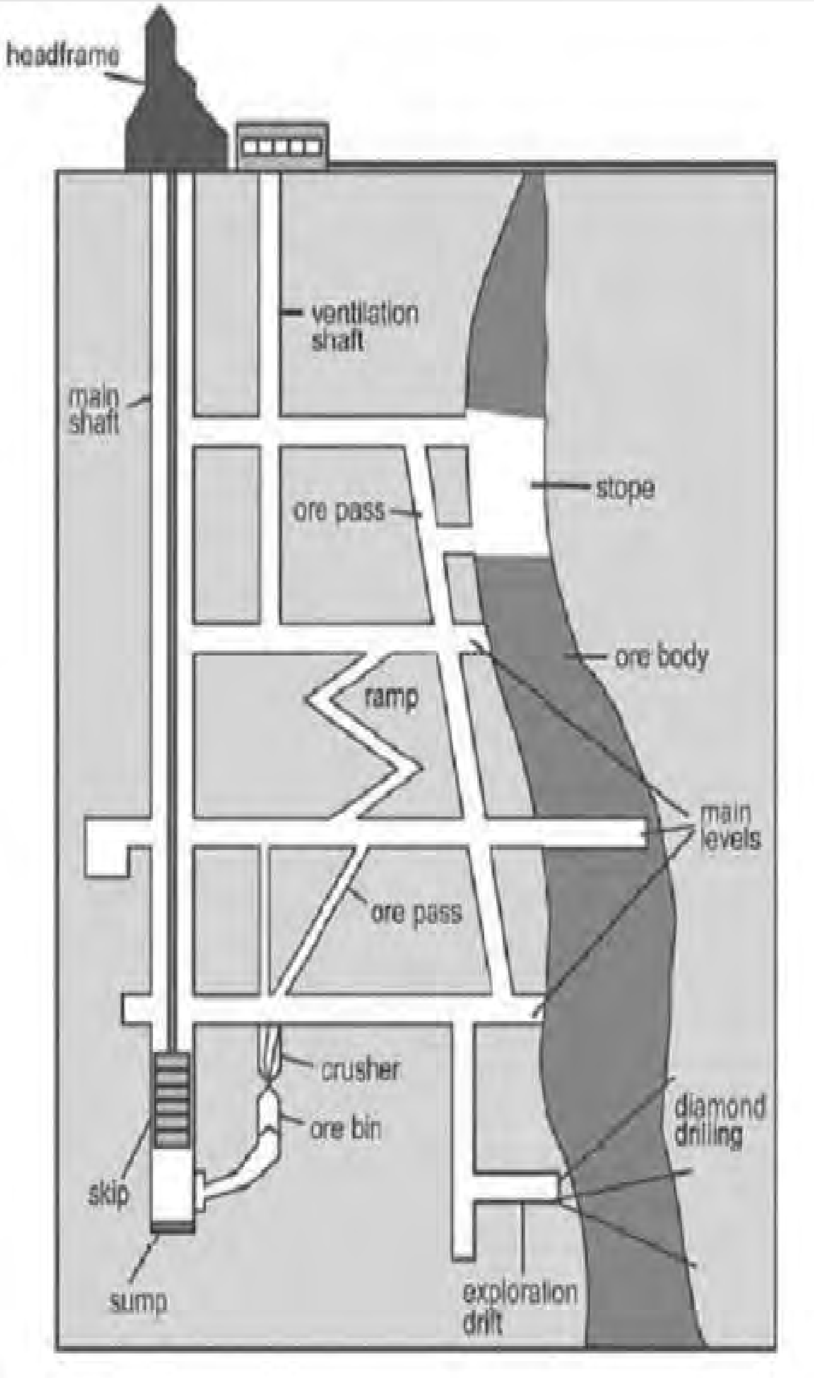
Huckleberry Copper Mine

Air and water penetrate fractured bedrock near the surface and the depth of surface weathering may be quite deep, especially in old landscapes in the tropics.

In Canada, glaciation has often removed most of the soft weathered rock.

Consequently, prior to mining most bedrock is initially unweathered and weathering starts when mining exposes walls and breaks bedrock into particles exposing rock surfaces.

Exceptions include Kemess South and North.

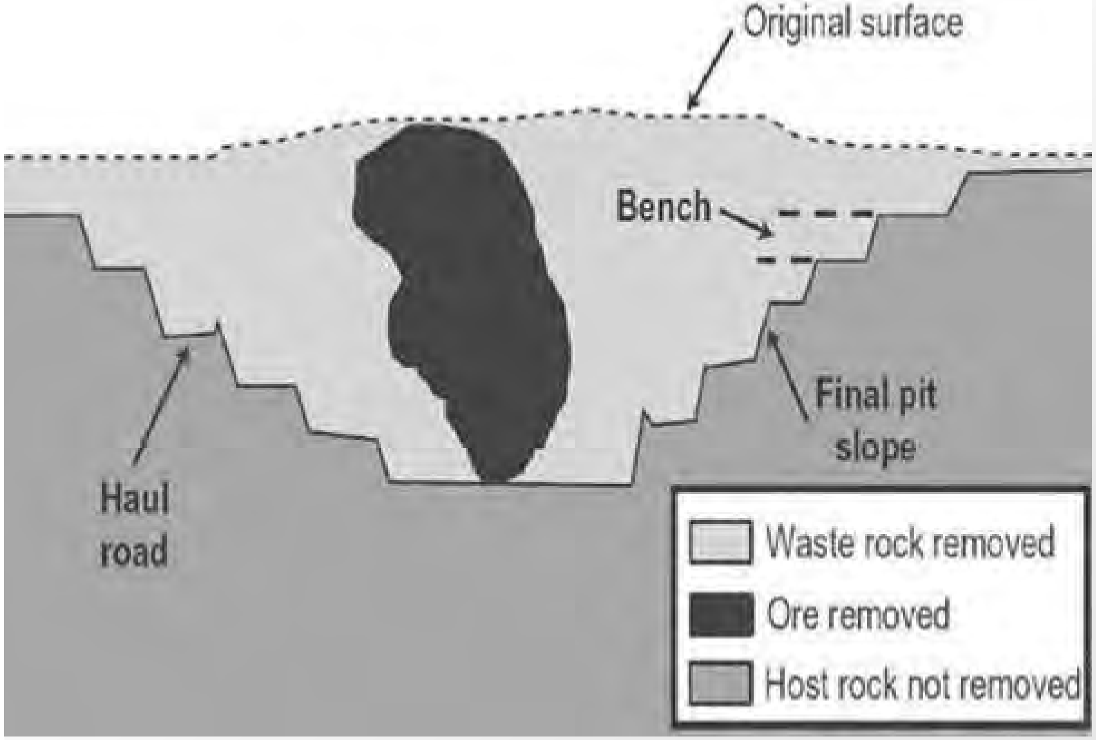


Mines have different shapes and sizes.

One major distinction is whether mines are open pits or underground.

Underground mines may make result in subsidence of the overlying ground.

Open pits extract more ore, but create far more waste rock.



Bedrock is most commonly drilled and blasted, using sufficient explosives to break bedrock into small enough sized particles for removal.

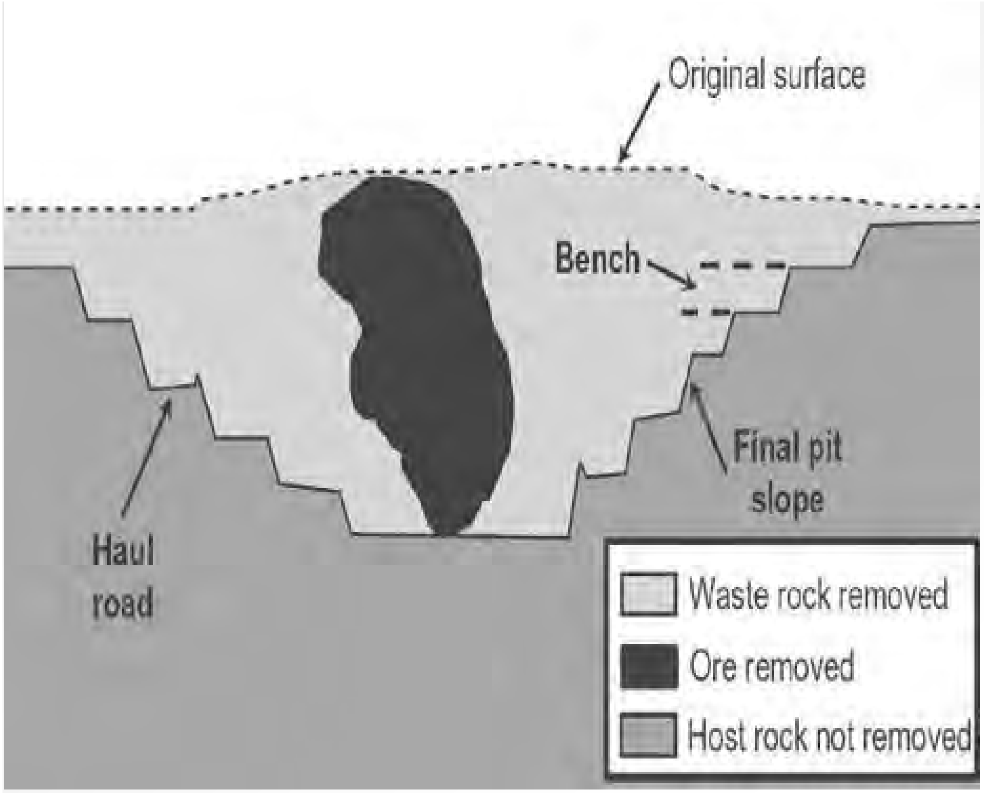
Removal is usually by trucks.

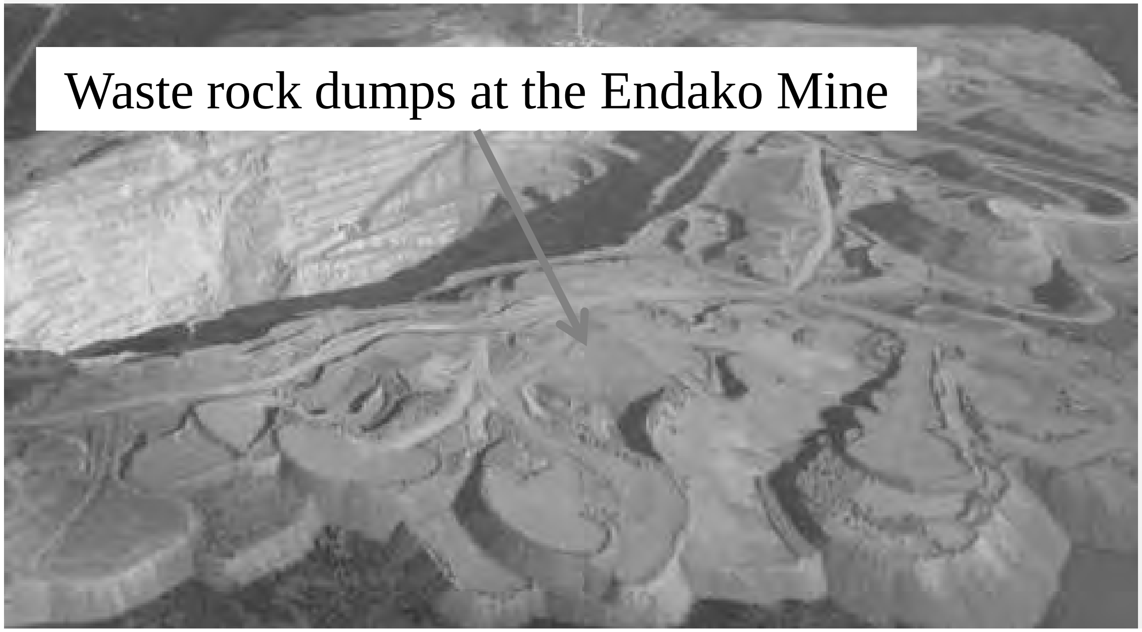
Ore versus Waste Rock

Rock containing the economic commodity is called ore.

Rock that has no economic value, and is excavated to access ore, is called waste rock.

For cost reasons, waste rock is usually placed close to and downhill of mine workings.



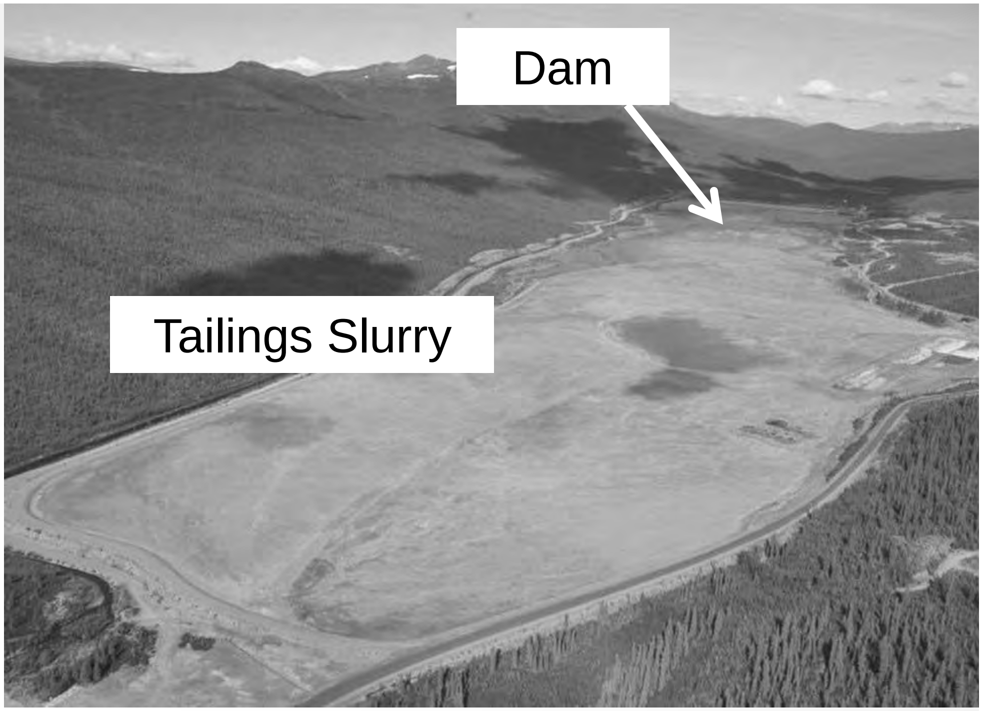

Waste rock dumps at the Endako Mine

The processing of ore starts with reduction of the blasted rock to small stone and then sand/silt-size.

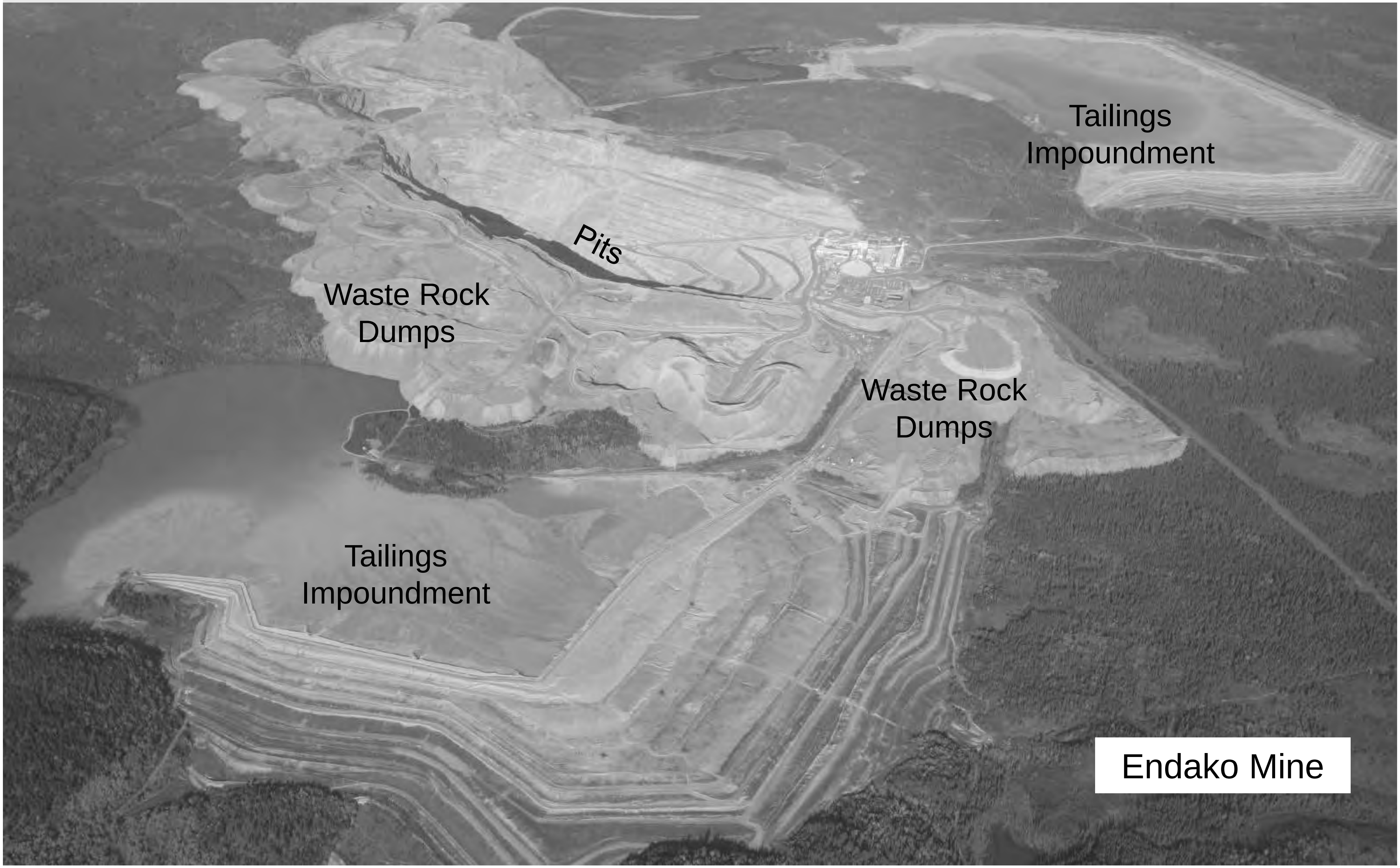
After the economic product is removed, the remainder is usually sand/silt-sized particles in a slurry.

The tailings slurry may be stored behind a dam in an impoundment.

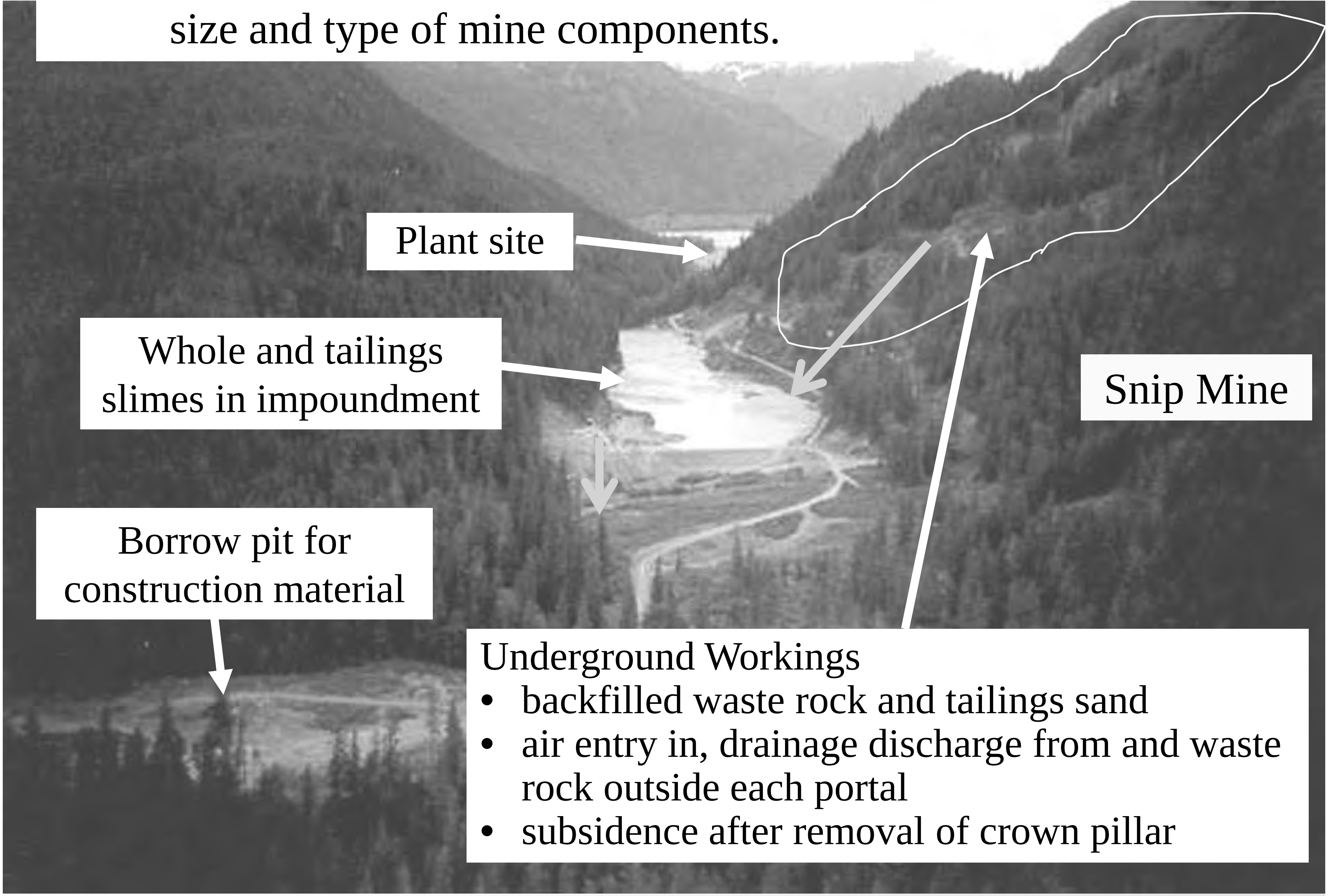
Tailings may be reworked for use as backfill or dried and stacked.



The largest components at most mines are the mine workings and the tailings and waste rock.



The type of mine will play a role in determining size and type of mine components.



Plant site

Whole and tailings slimes in impoundment

Borrow pit for construction material

Snip Mine

Underground Workings
- backfilled waste rock and tailings sand
- air entry in, drainage discharge from and waste rock outside each portal
- subsidence after removal of crown pillar

Mitigation Tools and Procedures:

Tools and procedures for prevention of impacts from sulphidic rock

ML/ARD Objectives

- drainage discharge limits;
- productive post-mining land use;
- sustainable use of national and corporate mineral resources by being cost effective and maintaining good regulatory and corporate images.

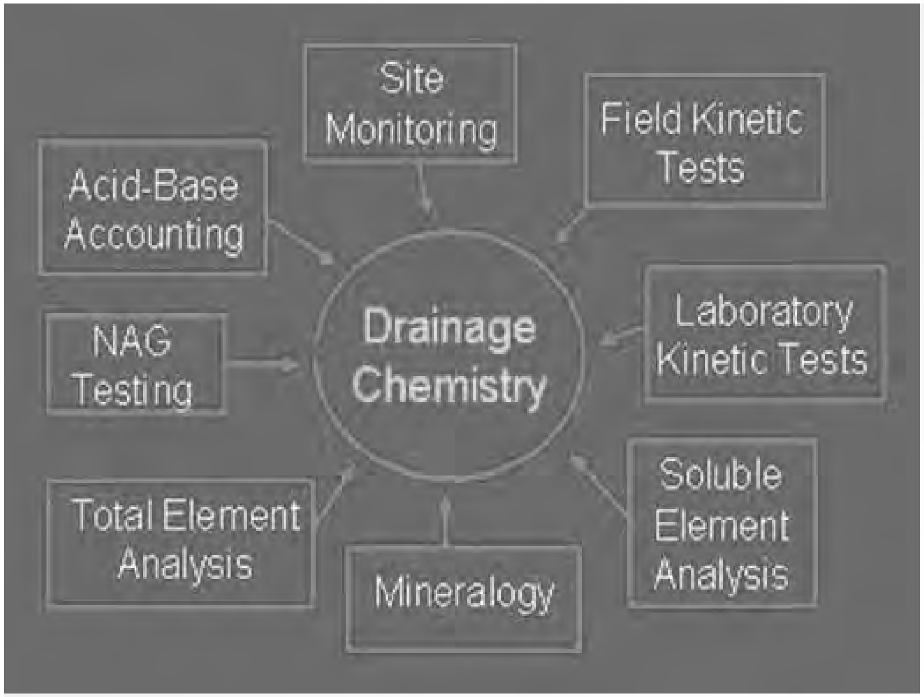
The first step in achieving the objectives is **prediction** of drainage chemistry and whether and what mitigation is needed.

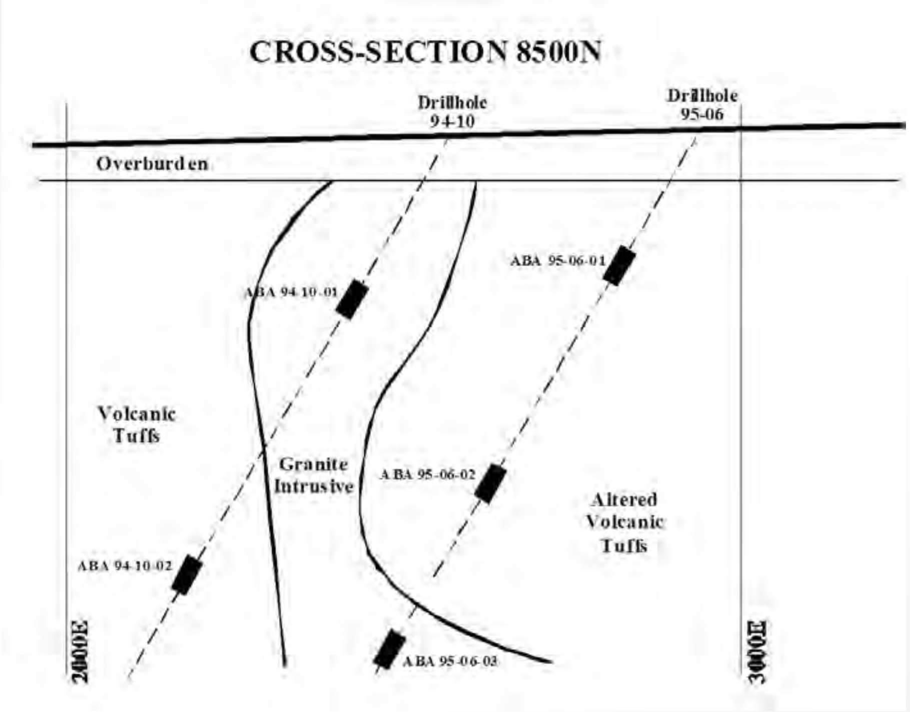
Prediction information is used to ensure:

- mining, processing, waste handling,
- mitigation, and
- additional prediction

are conducted in a way that prevents significant environmental impacts.

Prediction of Drainage Chemistry





Prediction of drainage chemistry requires:

- collection of geologic samples,
- a number of different static and kinetic tests of the samples, and
- interpretation of the sample results.

Samples should be collected from the entire range of contributing geologic materials and spatial area.

Sample locations should be plotted on geologic cross sections of the mine workings to demonstrate the geologic and spatial representation.

Analyses that measure sample composition are called ‘static tests’.

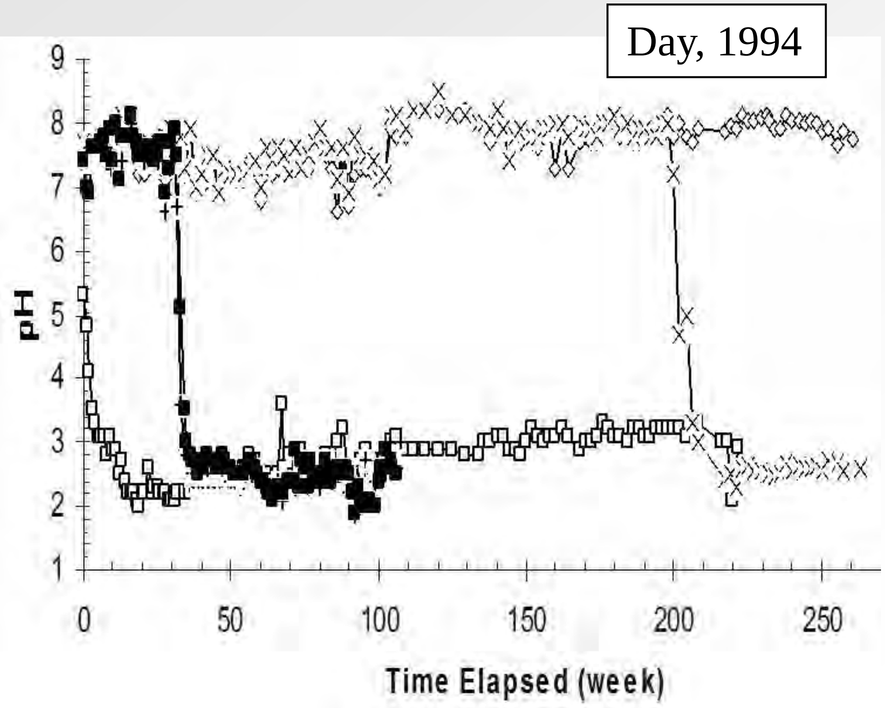
Properties of composition that are measured include:

- total elemental mass,
- soluble constituents,
- sulphur species and acid potential,
- neutralization potential,
- particle size and
- mineral composition and other mineralogical properties.

Measurement of sample composition provide most of the information used to predict drainage chemistry.

Soluble Constituents

Acidity



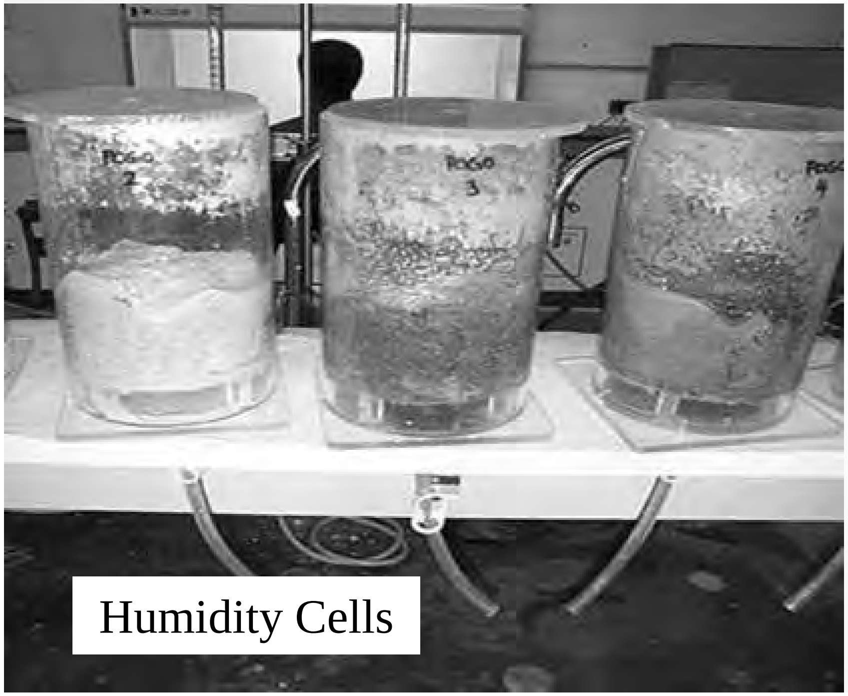
Day, 1994

Kinetic tests measure changes over time as a result of weathering.

Kinetic tests take considerable time and are generally run:

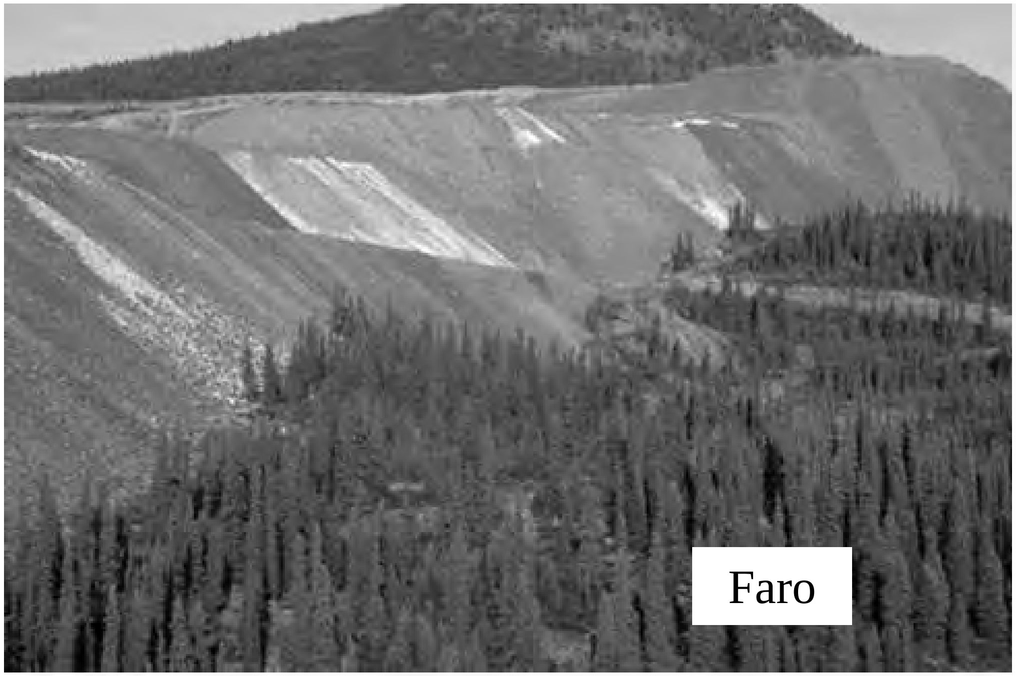
- on a subset of samples and
- to collect reaction rate or drainage chemistry data.

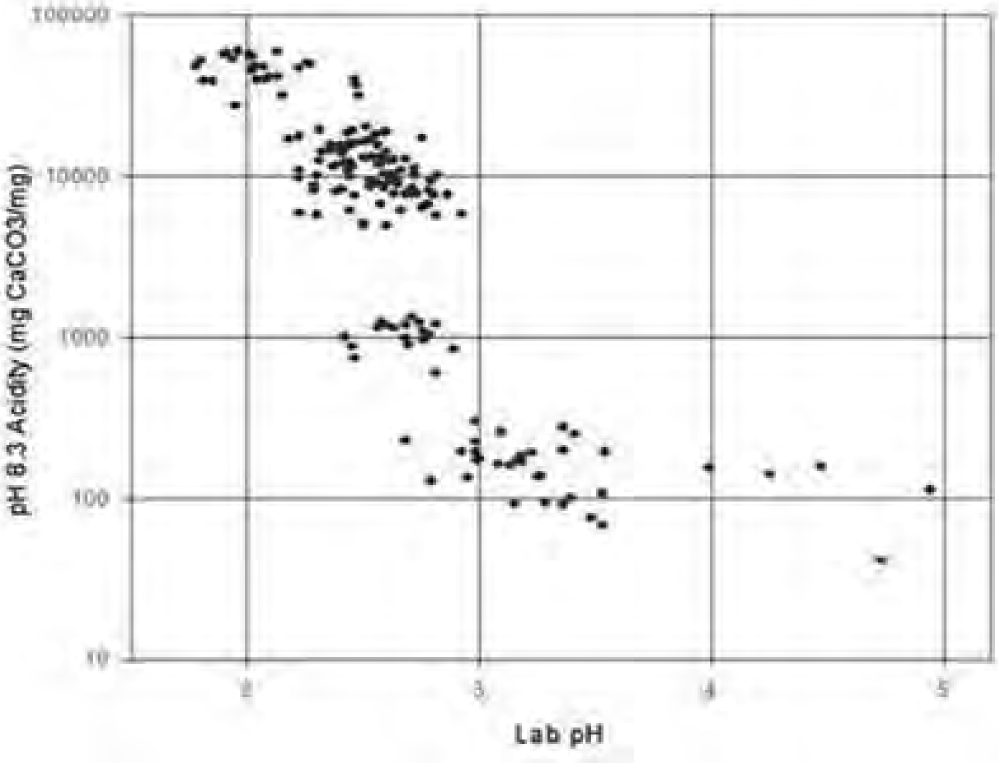
Examples of kinetic tests are humidity cells, columns and field pads.



Humidity Cells

Field Test Pads



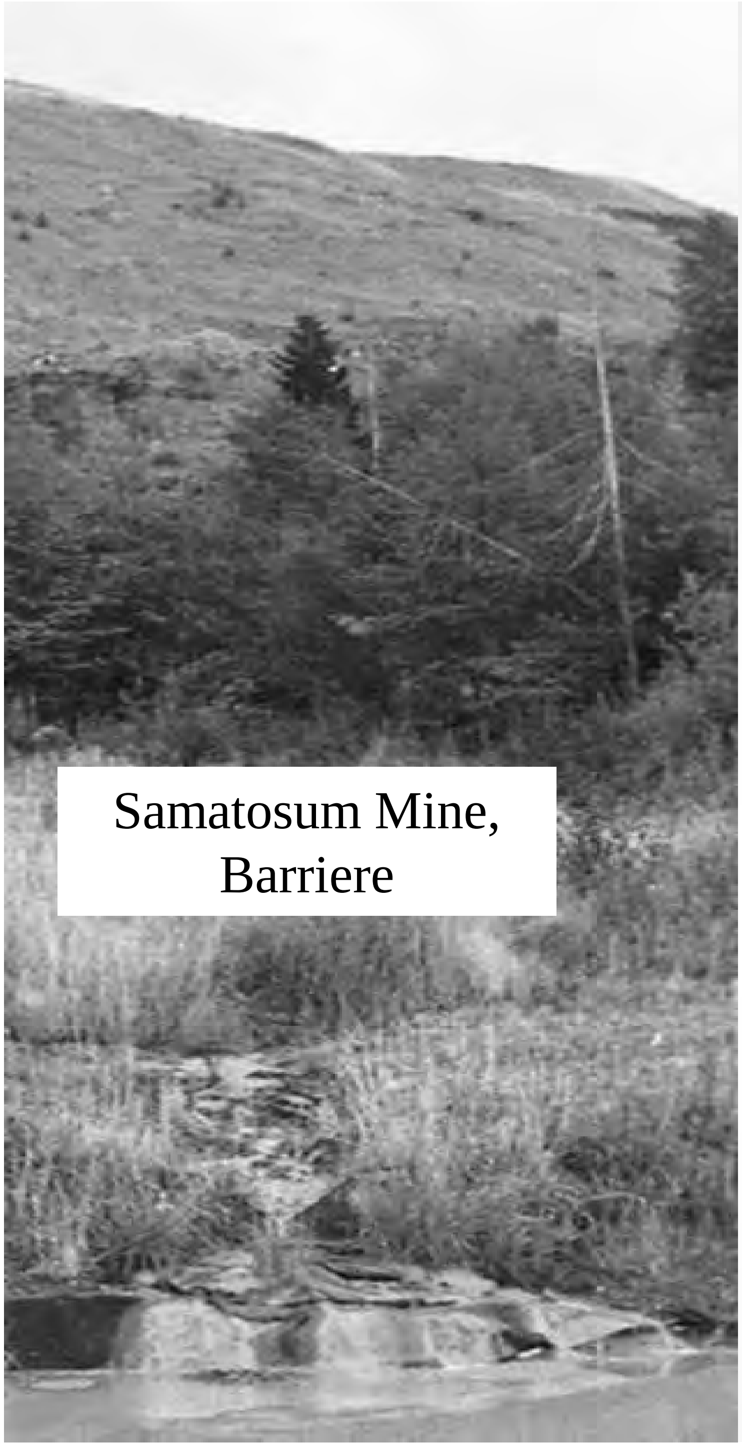


When conducting prediction, it is important to recognize that only a small portion of the geologic material may be responsible for the majority of the contaminants.

The majority of the acidity and contaminants from waste rock at Faro comes from the massive sulphide rock, which is 13% of the total mass.

Prediction should include:

- evaluation of the range and variability in contributing properties and processes and
- mapping the spatial variability of key geochemical properties.


Samatosum Mine, Barriere

Interpretation of prediction analysis and test results and calculation of elemental discharge rate requires scale-up from the laboratory to field-scale and consideration of drainage paths and outputs, and therefore hydrology is as important as chemistry.

Future drainage chemistry and elemental discharge rate should be predicted for each:

- geologic material,
- mine components (e.g., waste rock and tailings) and
- weathering conditions (e.g., aerial or flooded).

Not all prediction questions can be answered prior to mining or closure. Operational and post-closure studies are needed to verify predictions, address information gaps, and reduce costs and risks.

Mitigation

The primary options for mitigation are:

- underwater disposal,
- dry cover and divert inputs of runoff and groundwater,
- treat drainage, and
- modifications to material composition or storage conditions.

Each method:

- uses different mechanism;
- targets different properties and processes; and
- differs in its effectiveness, strengths, weaknesses, and associated risks.

Underwater (Subaqueous) Disposal

Due to lower solubility, even when water is well aerated, the concentration of O_2 in water is ~ 30 times lower than in air (8-12 mg/L vs. 285 mg/L).

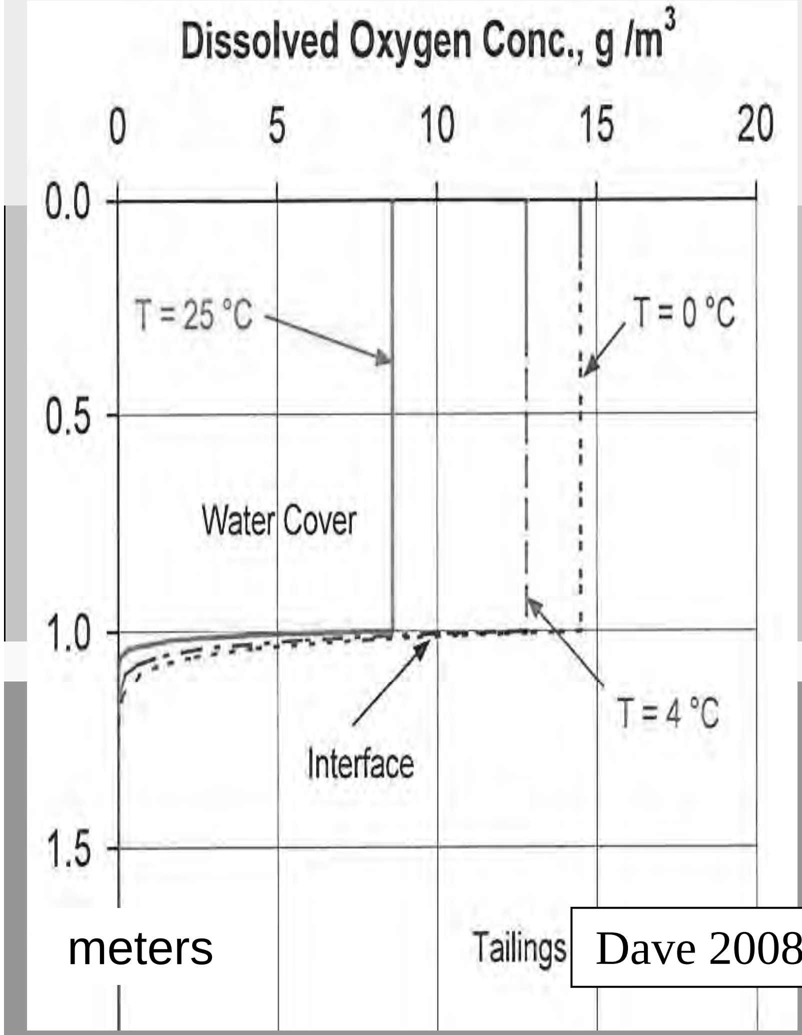
Oxygen entry into the underlying subaqueous materials is primarily by molecular diffusion and the diffusivity of O_2 in water at 20°C is ~10,000 slower than in air.

The combined effect of low oxygen concentrations and slow diffusion results in an up to 300,000 times reduction of oxygen ingress into water-filled pores of subaqueous tailings compared to sub-aerially.

Even under less ideal conditions, flooding results in a 1000 times reduction in the rate of sulphide oxidation.

Subaqueous Disposal

Due to the low rate of O_2 ingress, dissolved O_2 is typically absent in the pores of flooded waste within a few centimetres of the sediment-water interface.



Dave 2008

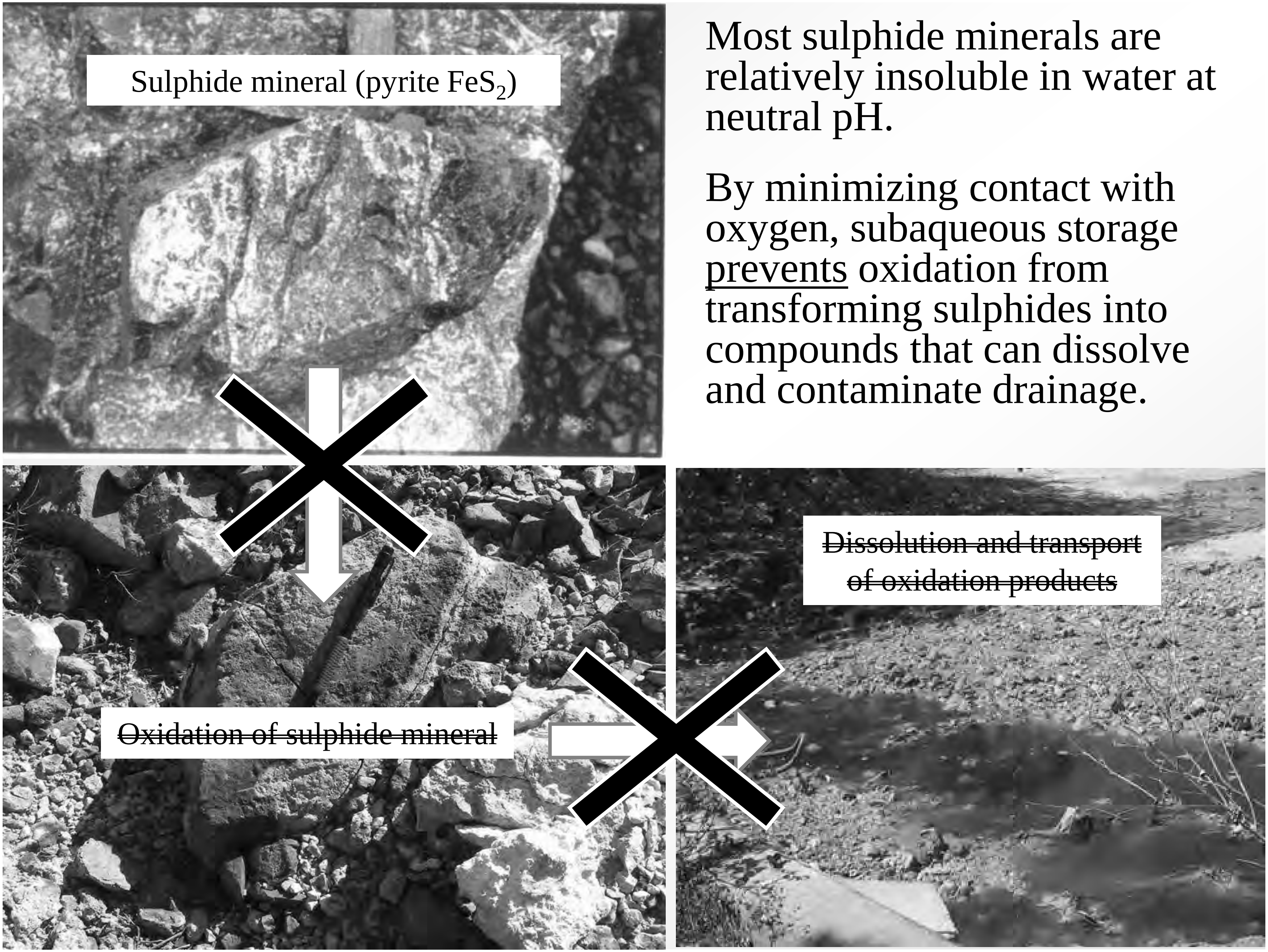
Water Cover

Oxidized Layer

Un-oxidized Mine Material

Most sulphide minerals are relatively insoluble in water at neutral pH.

By minimizing contact with oxygen, subaqueous storage prevents oxidation from transforming sulphides into compounds that can dissolve and contaminate drainage.



Sulphide mineral (pyrite FeS_2)

~~Oxidation of sulphide mineral~~

~~Dissolution and transport of oxidation products~~

Equity Silver Mine

Underwater storage can occur behind a constructed dam, in mine workings, or in natural water bodies, such as lakes.

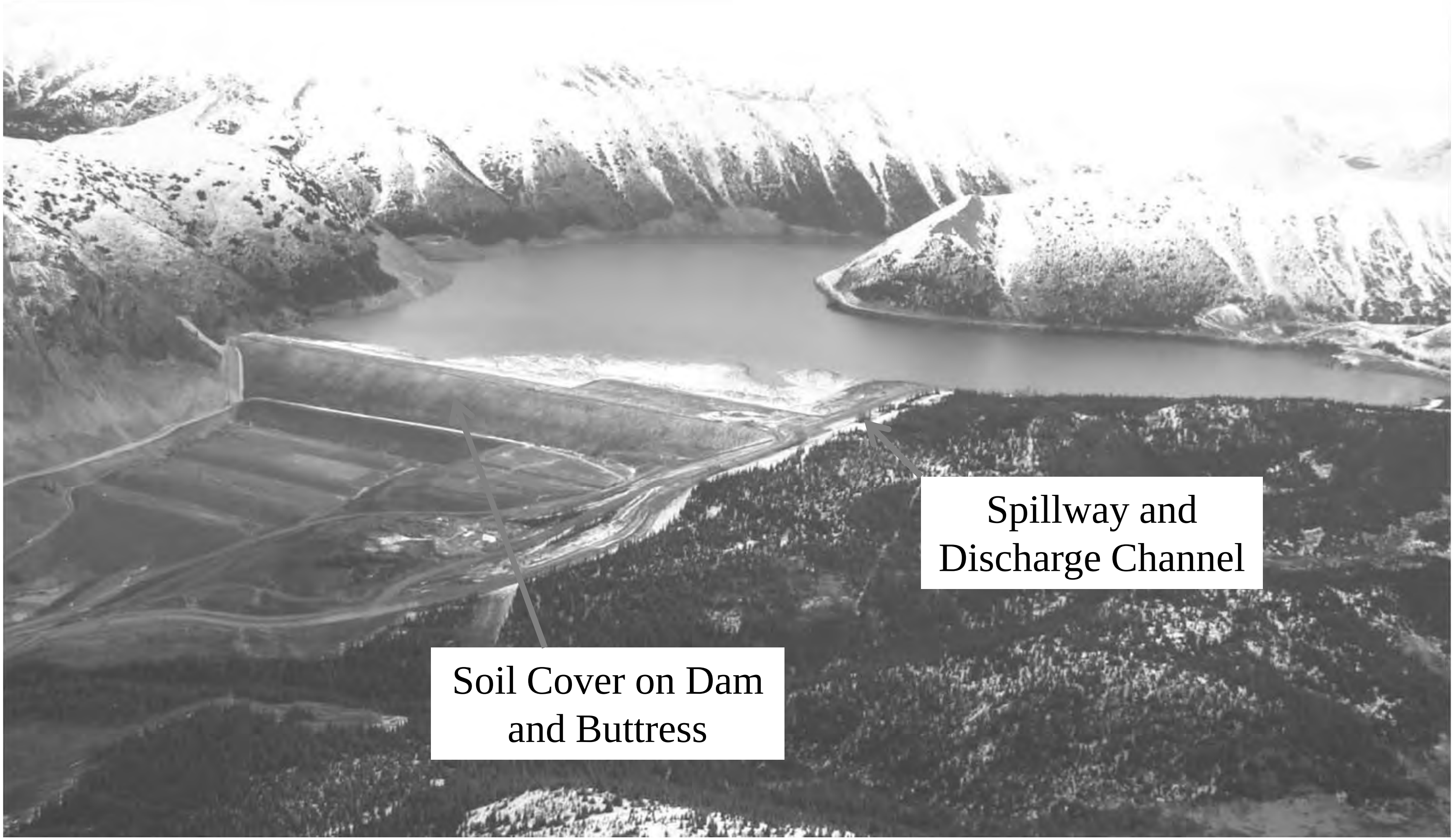
Advantages are the almost complete prevention of sulphide oxidation and the relatively minor closure <u>costs</u> of maintaining and monitoring dams and other water management features.

Eskay Creek Mine

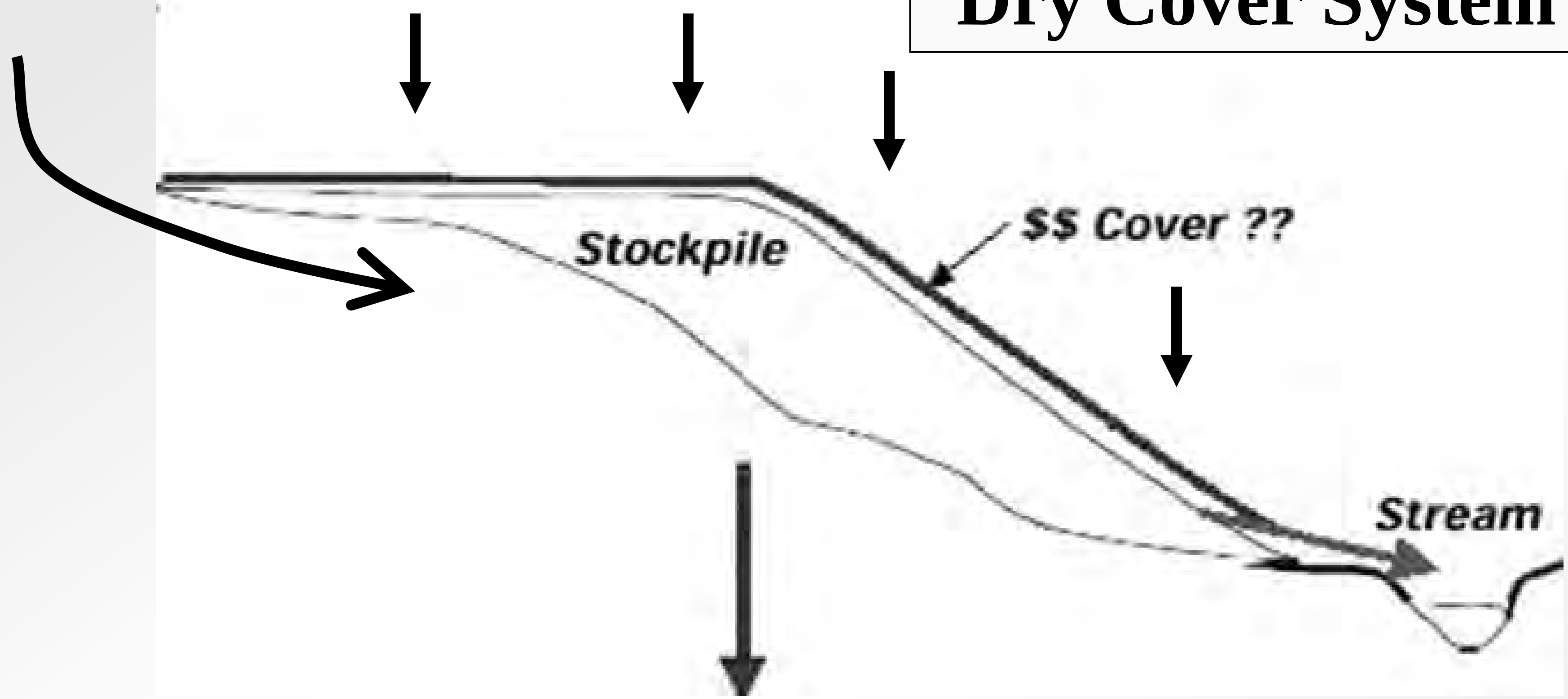
The major disadvantage is the catastrophic potential consequences in the event of a dam failure. Underwater storage does not reduce oxidation if sulphide materials are exposed in the future. Where dams are used, the geochemical risk with sulphides is converted to a geotechnical risk with dams.

Post-closure monitoring and maintenance of man-made structures are essential to ensure mine materials remain permanently flooded.

Maintenance and repair need to be proactive.



Dry Cover System



The objective of a dry cover system is to reduce infiltration of oxygen and/or water. Performance of dry cover system depends on the rate of:

- infiltration through the cover; and
- ingress from the sides underneath the cover.

Consequently, a cover system consists of the cover itself and measures, such as diversions, to prevent lateral ingress.

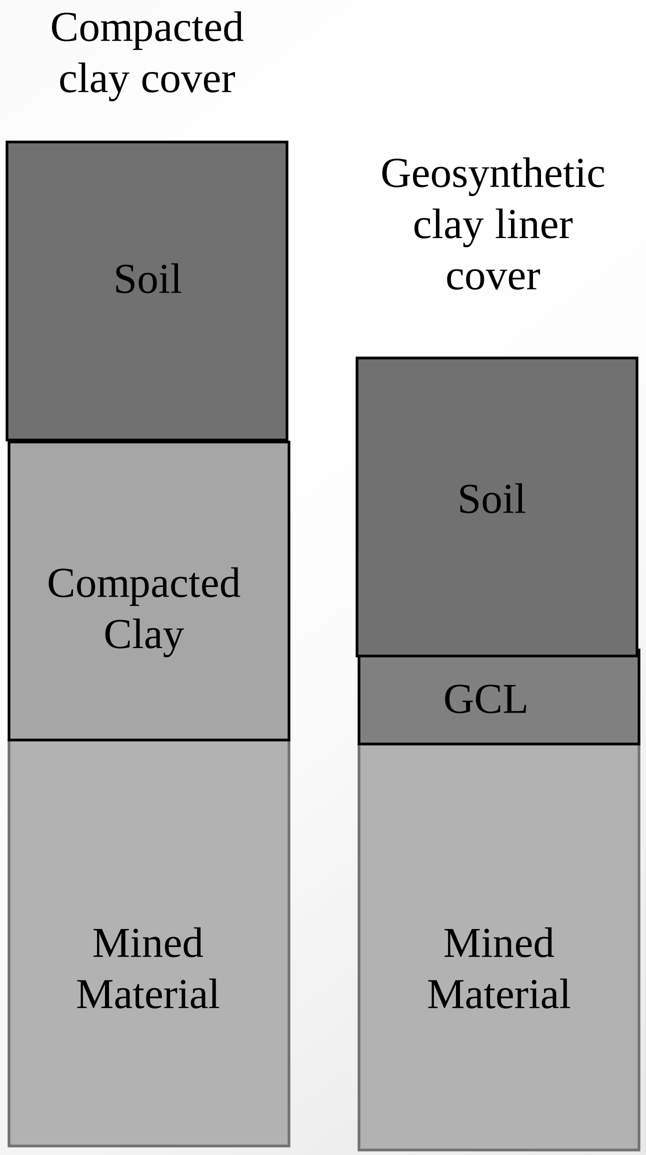
Barrier Cover

This is the “classic” cover type.

The barrier layer is constructed from compacted, low permeability soil (e.g., glacial till), geomembrane, asphalt or a geosynthetic clay liner (GCL).

The barrier layer typically needs an overlying protective layer and may need a protective underlying layer to prevent punctures.

A coarse layer underneath creates a capillary barrier that increases saturation of the cover and prevents contamination of the cover by the mine material below.



Compacted clay cover

Soil

Compacted Clay

Mined Material

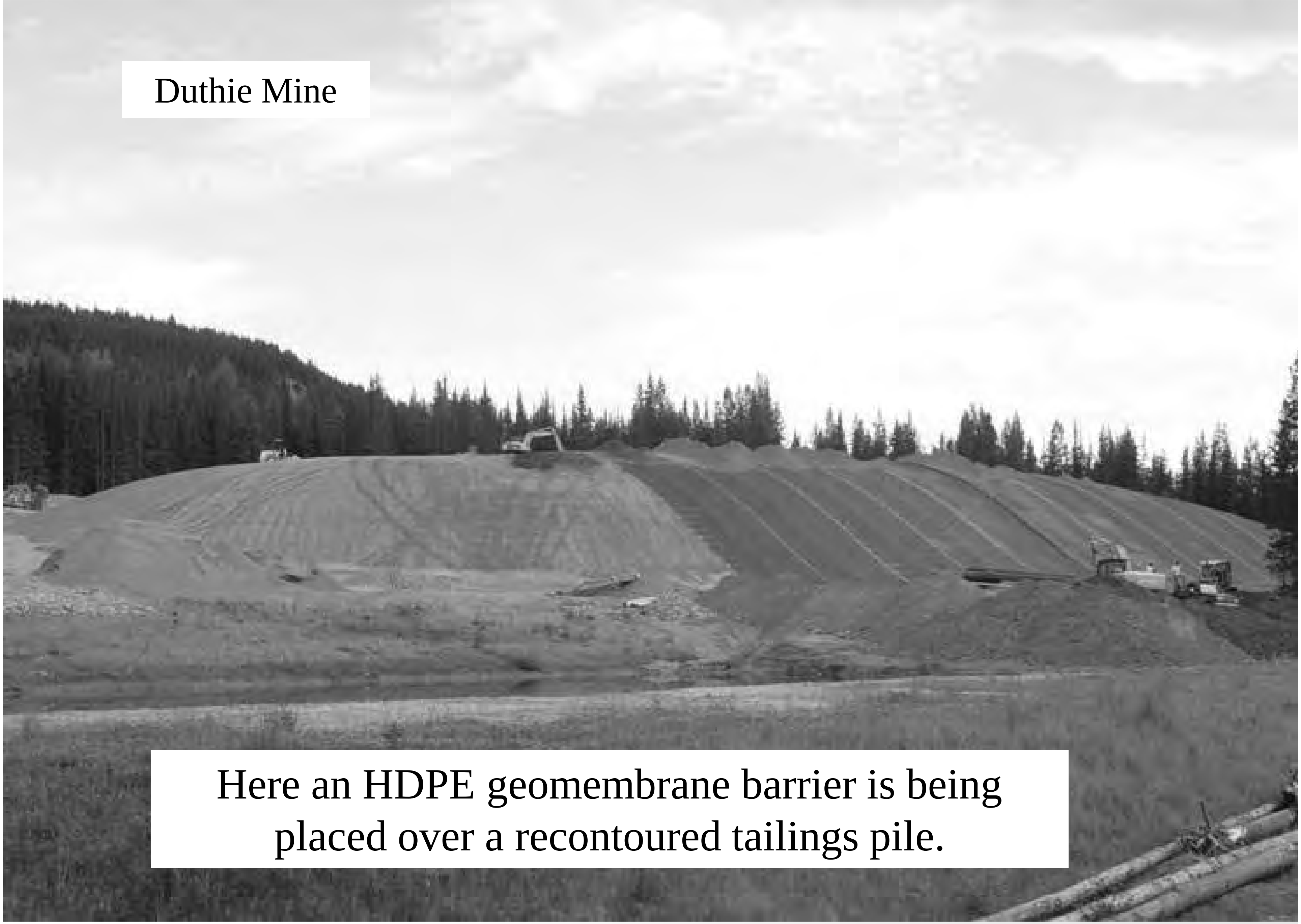
Geosynthetic clay liner cover

Soil

GCL

Mined Material

Soil, if suitable material is available, is often the first choice as a barrier layer material due in part to cost considerations (Ayers et al. 2009).



Duthie Mine

Here an HDPE geomembrane barrier is being placed over a recontoured tailings pile.

Store-and-Release Cover

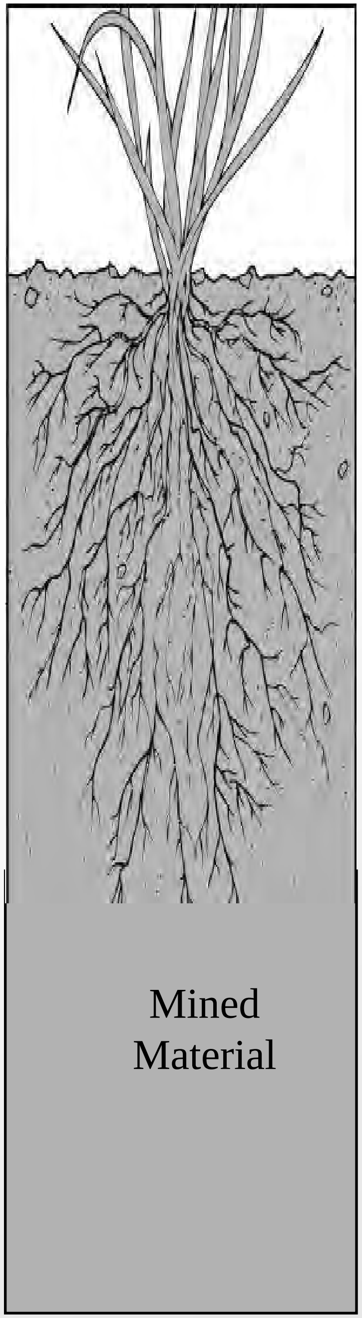
Store-and-Release is the other main cover type.

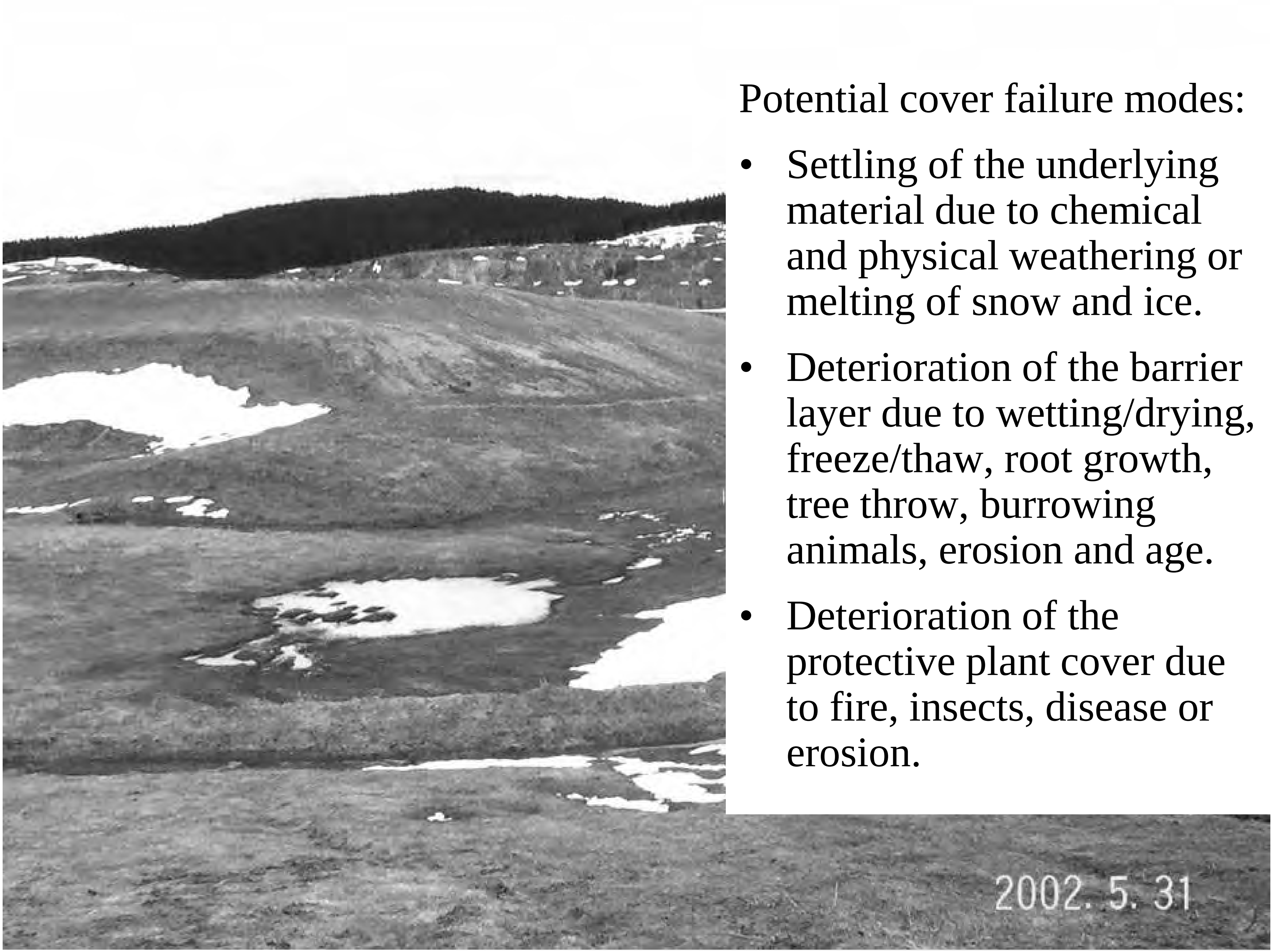
Incident precipitation is removed by evaporation and evapotranspiration

Ideally, evapotranspiration exceeds precipitation – an arid environment with a high negative water balance – and the cover depth is sufficient to store precipitation until it is removed.

Store-and-release may supplement the performance of the barrier layer in more humid regions.

Store-and-release covers are less susceptible to cracking or other forms of cover damage than other cover types.





Potential cover failure modes:

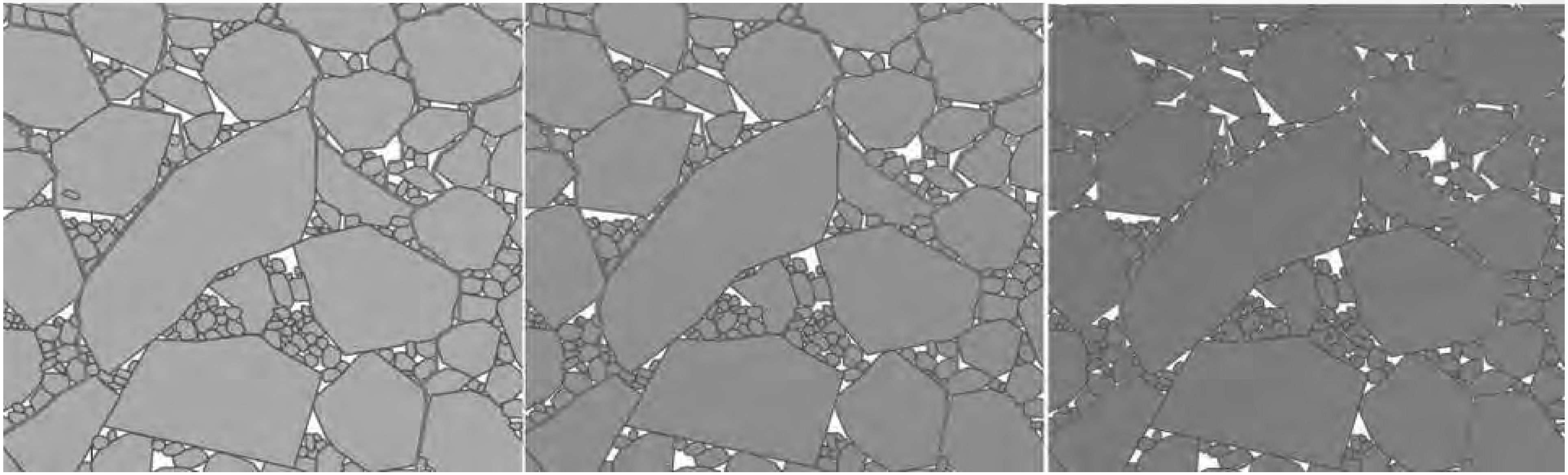
- Settling of the underlying material due to chemical and physical weathering or melting of snow and ice.
- Deterioration of the barrier layer due to wetting/drying, freeze/thaw, root growth, tree throw, burrowing animals, erosion and age.
- Deterioration of the protective plant cover due to fire, insects, disease or erosion.

Equity Silver Mine

Unlike subaqueous disposal, the reduction in contaminant release by a cover is often not enough to preclude drainage treatment, especially if there is significant lateral air and groundwater input.

Caution: Continued oxidation of waste rock underneath a cover will increase the mass of soluble metals available for release if in the future the cover deteriorates or upslope drainage inputs increase.

So just like dams for subaqueous disposal, it is critical to sustain cover performance and the diversion of upslope drainage.

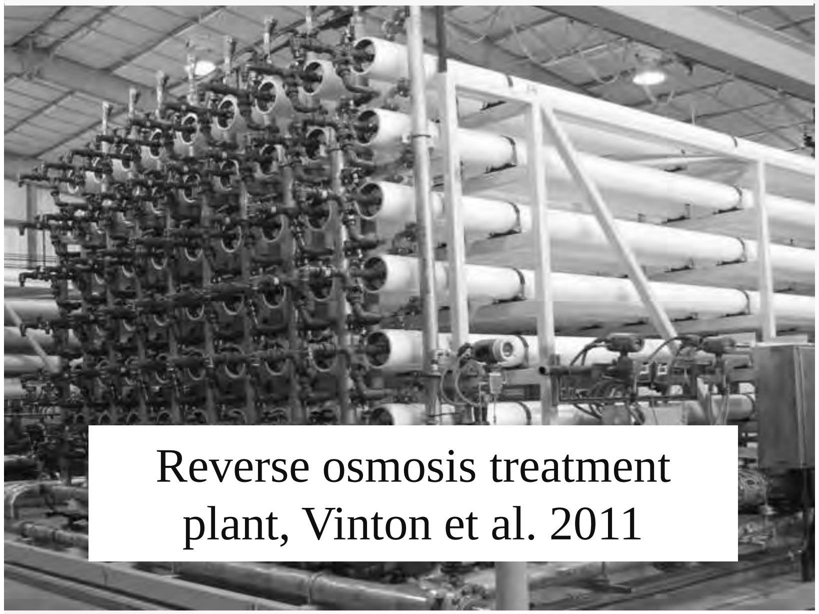


Drainage Treatment

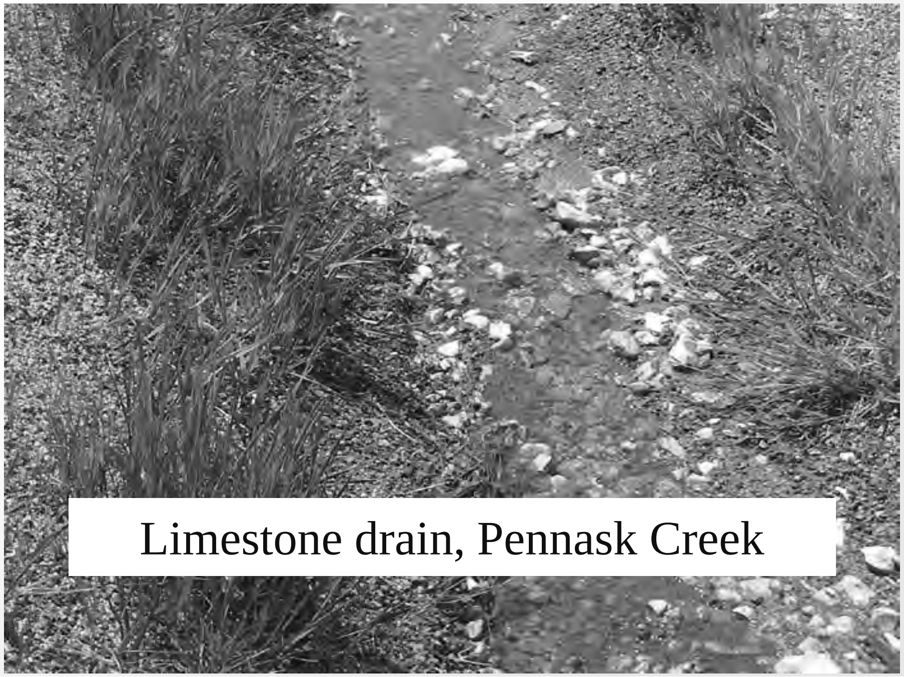
Treatment removes contaminants from water, most commonly by precipitation.

Treatment processes:

- may be chemical, physical-chemical (filtration) or biological; and
- operation and maintenance of treatment facilities may be continuous or periodic, but is never completely passive if the performance needs to be sustained.


Reverse osmosis treatment plant, Vinton et al. 2011


Lime treatment plant, Cape Breton

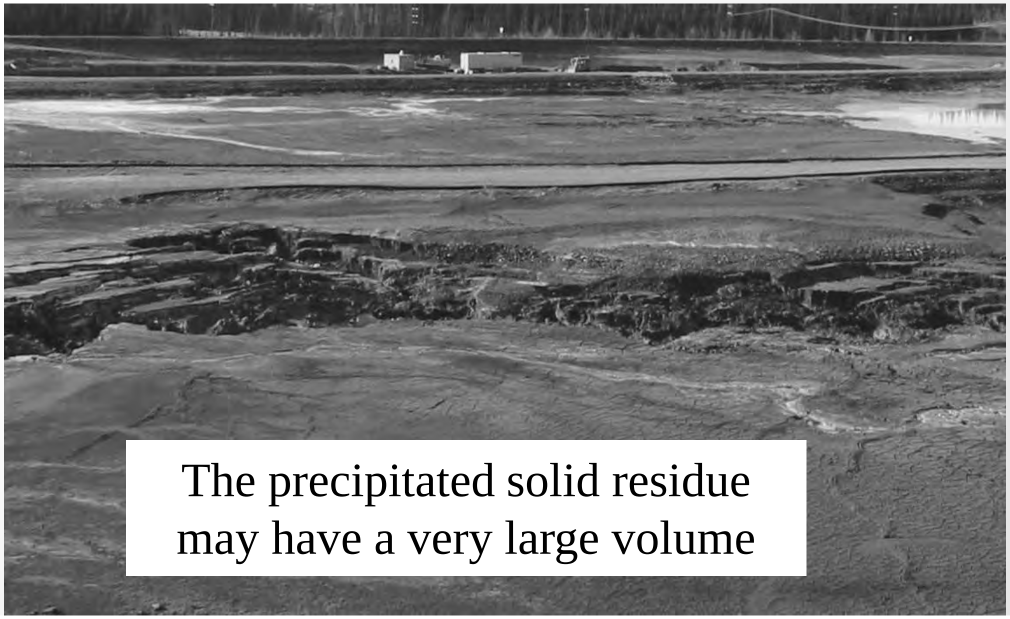

Limestone drain, Pennask Creek

In addition to treatment itself, treatment requires:

- collection and storage of contaminated drainage
- diversion of clean water
- separation of precipitated contaminants from treated effluent and controlled discharge of treated effluent
- disposal of resulting solid treatment wastes

Storage for the contaminated drainage is needed during plant maintenance and repairs and when runoff exceeds treatment capacity.

A clarifier is used to separate precipitated contaminants



The precipitated solid residue may have a very large volume

Chemical treatment reagents include alkali, such as lime, to raise pH and remove metals and ferric sulphate or chloride to remove anions Mo, As, Sb and Se.

Process control is relatively simple, rapid and reliable with reactive chemical reagents and the treatment rate can be moderated to handle changing flow and contaminant concentrations.

HDS lime treatment at Equity Mine

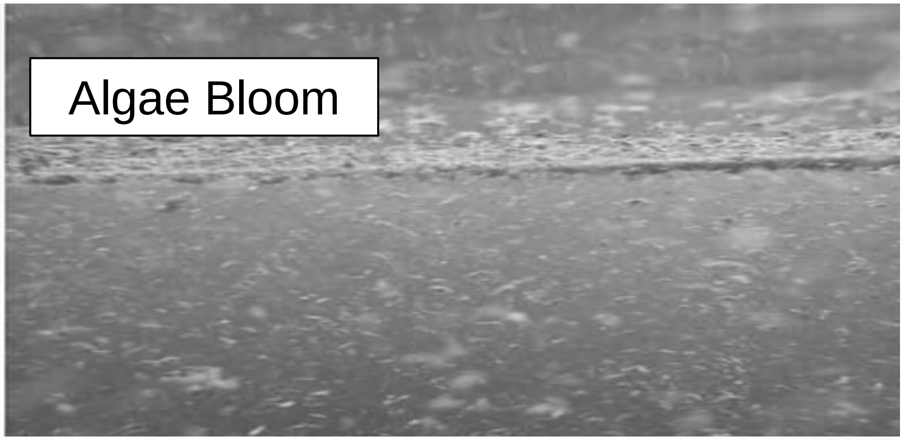
Arsenic treatment at Giant Mine

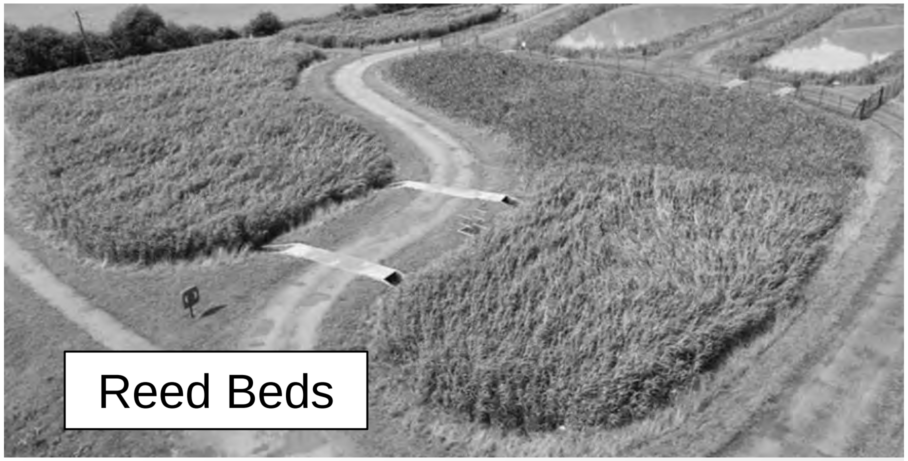
Biological treatment includes:

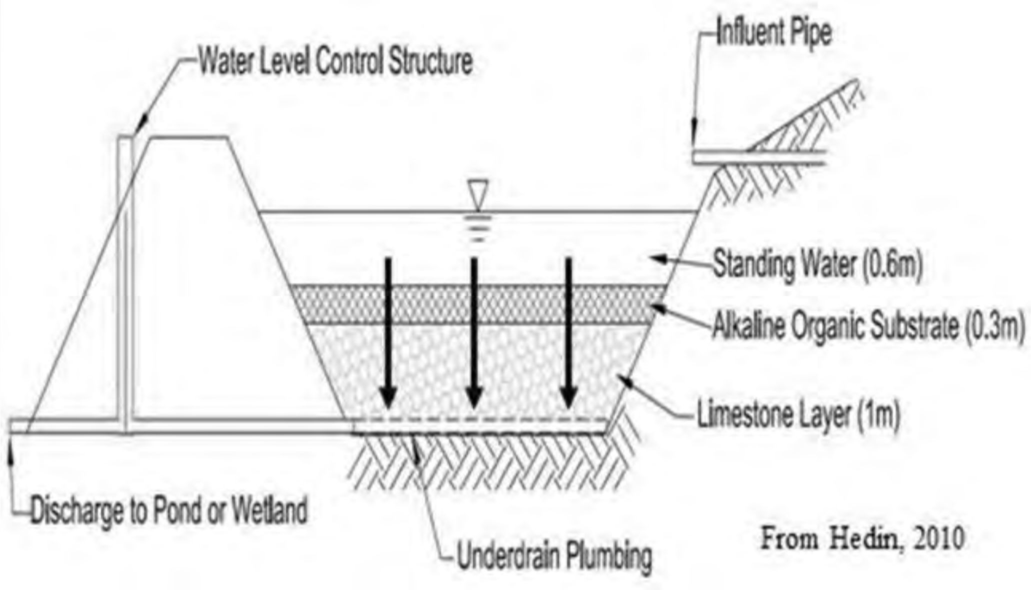
- adsorption to organic surfaces, such as algae blooms,
- reed beds for removal of precipitated iron by aerating drainage emerging from underground mines and
- sulphate reduction - carbon source removes oxygen and creates sufficiently reducing conditions for sulphate reducing bacteria to form sulphide and the sulphide then precipitates metals.

$$H_2S + Zn^{2+} \rightarrow ZnS + 2H^+$$

The sulphate reduction plant at the Raglan Mine is used for commercial recovery of nickel.







From Hedin, 2010

Key features with any form of treatment include:

- treatment rate capable of matching maximum contaminant loads and
- plumbing capable of matching max flow rates.

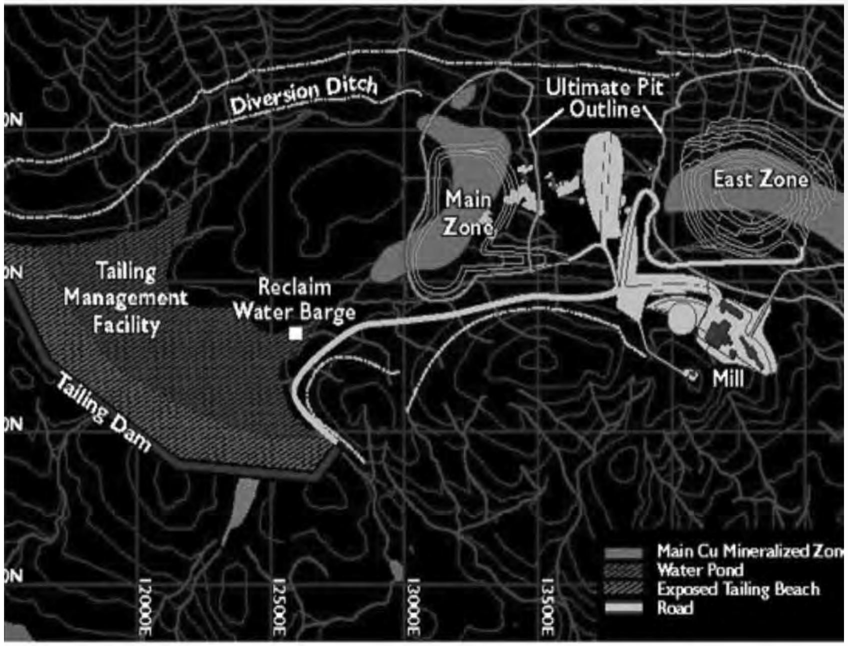
Treatment wetland proposed as a contingency measure often cannot sustain the necessary reaction rate and sediment conductivity, and much of the water and metals passes over the top largely untreated, especially during snow melt.

A major potential limitation of a treatment wetland is surface plugging reducing downward vertical flow

Treatment Conundrum

- Reliability and effectiveness make perpetual chemical treatment the first choice to protect the environment in the event of failures.
- High long-term costs, secondary waste production, limited capacity for post-mine site use and risk of spills often make perpetual treatment the mitigation strategy of last resort.

Modify Storage Conditions and Material Composition



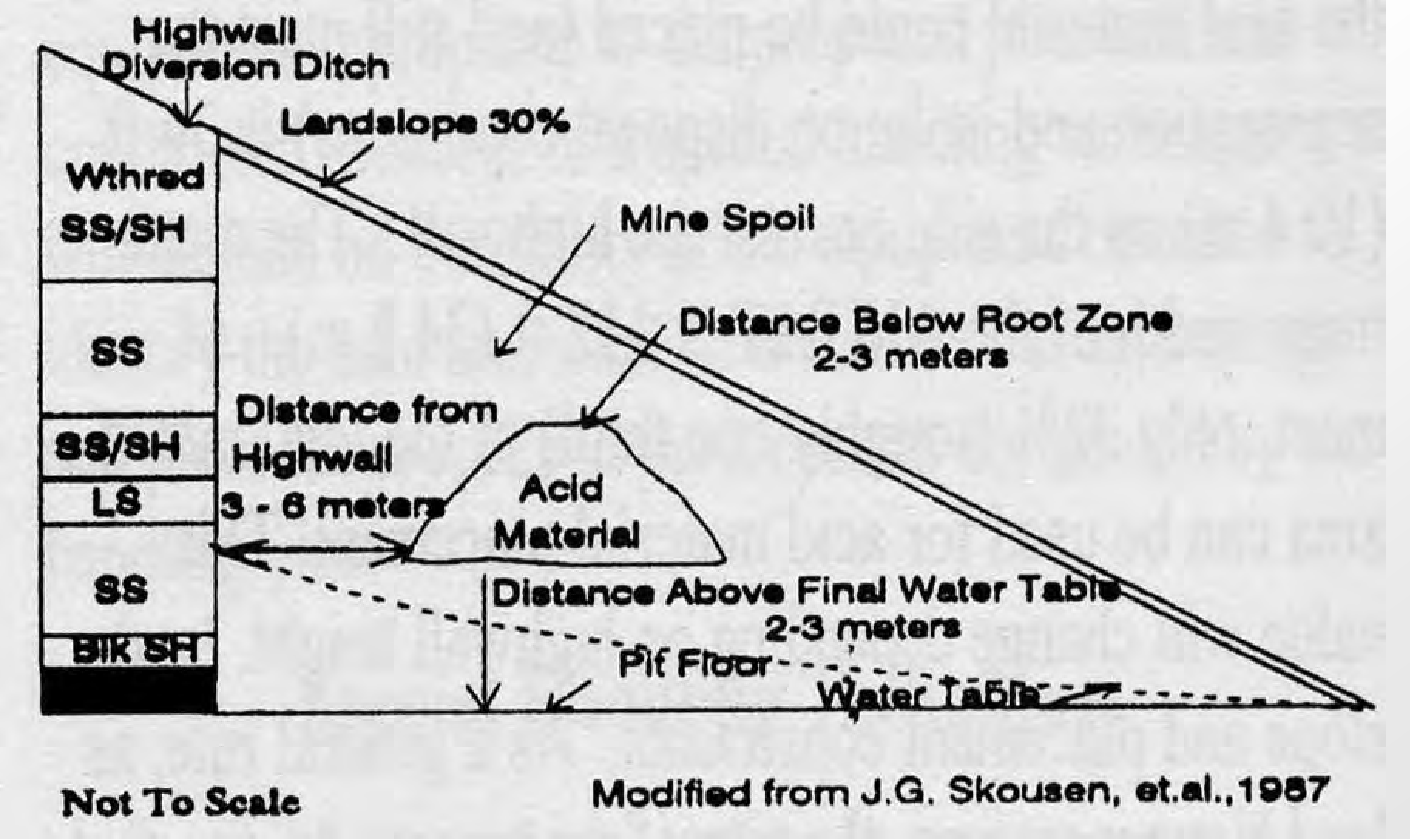
Similar to other forms of mitigation, modifications to storage and material composition have major potential benefits but may not be technically or financially feasible and may create other challenges and risks.

Backfilling tailings and waste rock into mine workings may potentially avoid or reduce:

- containment structures requiring perpetual maintenance,
- air and drainage inputs,
- spatial extent of the mine, and
- need for other forms mitigation.

Huckleberry backfilled both waste rock and tailings into their pits.

Hydrologic Isolation minimizes leaching of problematic materials by their placement location and/or method. In the example below, leaching is minimized by placing PAG waste rock above the zone leached by groundwater (and below a low permeability cover).



Modified from J.G. Skousen, et.al.,1987


Segregation of PAG and non-PAG waste rock

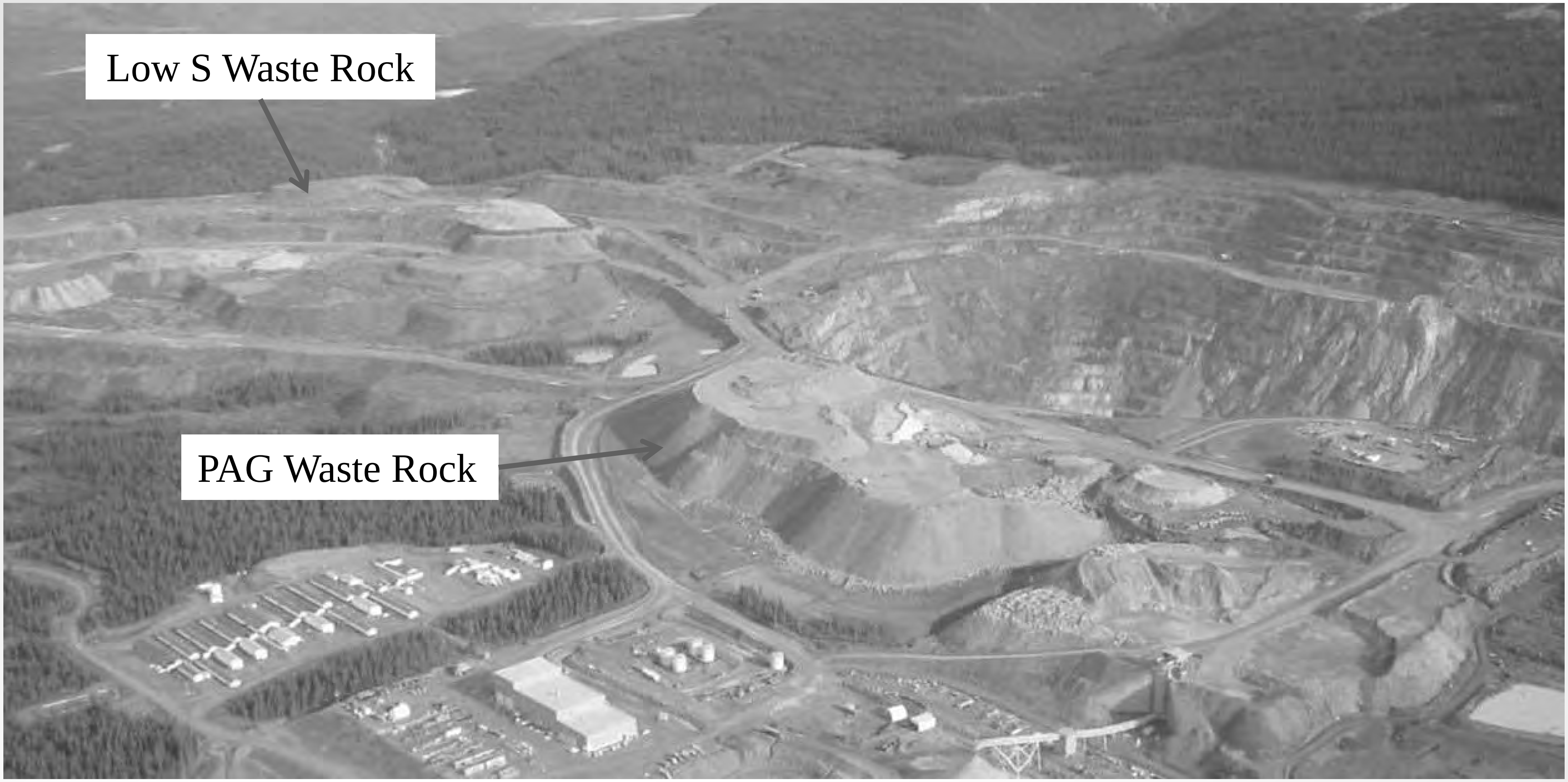

XRF used to ID and segregate low from high-arsenic waste rock

Segregation may reduce mitigation requirements by:

- reducing the mass of materials with onerous mitigation requirements and
- separating materials with different mitigation needs.

Segregation is only feasible if materials with different mitigation requirements can be reliably and rapidly operationally identified and physically separated.

On-site laboratory facilities are usually required for rapid operational segregation.



Kemess segregated PAG waste rock from low S, non-PAG waste rock so PAG could be backfilled into the pit at closure and flooded.

Although some was non-PAG, Takla Volcanic waste rock was handled as if it was all PAG because the presence of FeCO3 made accurate rapid on-site measurement of the ARD potential impossible.

Blending: The objective in blending is to combine poor quality material with better quality material to create a sufficiently good quality composite (e.g., net-neutral) .

Again requires detailed material characterization and careful handling.

The main impediment is the difficulty in physically mixing the two materials sufficiently to prevent the occurrence of <u>pockets</u> of poor quality material.

Coal mines in NE British Columbia push PAG with an excess of non-PAG waste rock onto the advancing slope to create a well mixed non-PAG composite.

A potential limitation with blending is that preventing acidic drainage does not prevent neutral pH problems (e.g., elevated Zn).

Desulphurized tailings slimes used to prevent air entry into PAG tailings.

Desulphurize Tailings

Modifications to mill processes can remove sulphides reducing the ML/ARD potential of tailings.

Low sulphide tailings may be used as a cover or construction material.

Residual high sulphide tailings can be placed underwater or underground.

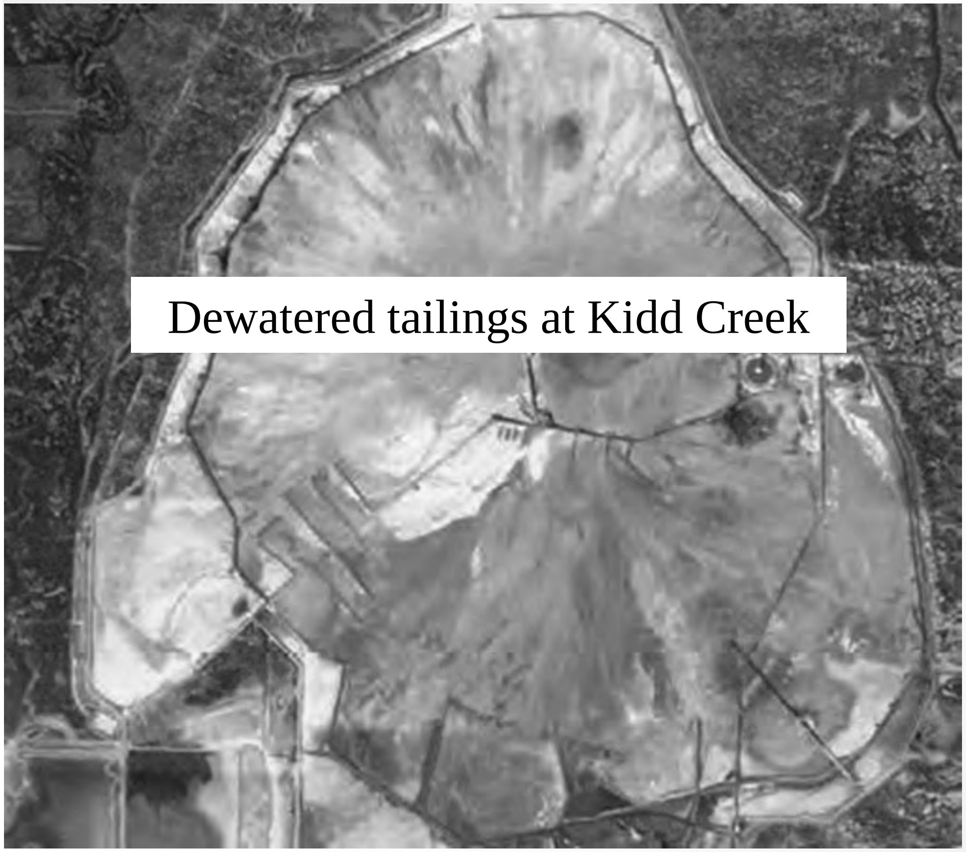
Desulphurized tailings sand used to buttress this dam

Dewatering – reduces tailings water content, but does not totally remove drainage.

Dewatering enhances recovery of process reagents, reduces ice formation and loss of water to the environment by evaporation and seepage, and prevents segregation of sand and silt, reducing air entry.

Dewatering may also increase tailings strength, which avoids or reduces size of retaining dams and potential dam failure scenarios. Greater strength also enables tailings use underground as backfill.


Filtered Tailings


Dewatered tailings at Kidd Creek

Challenges with dewatered tails:

- rapid sulphide oxidation creates drainage problems;
- mass wasting if wet, need to keep dry; and
- susceptible to wind erosion, need dust suppression.

Oxidation of tailings at the surface may produce extremely acidic drainage.

Closure plan for dewatered tailings typically includes dry covers and drainage treatment, with their associted costs and risks.

Conclusions:

Sustained extraction of sulphidic mineral resources requires mines, government to address the major challenges that exist:

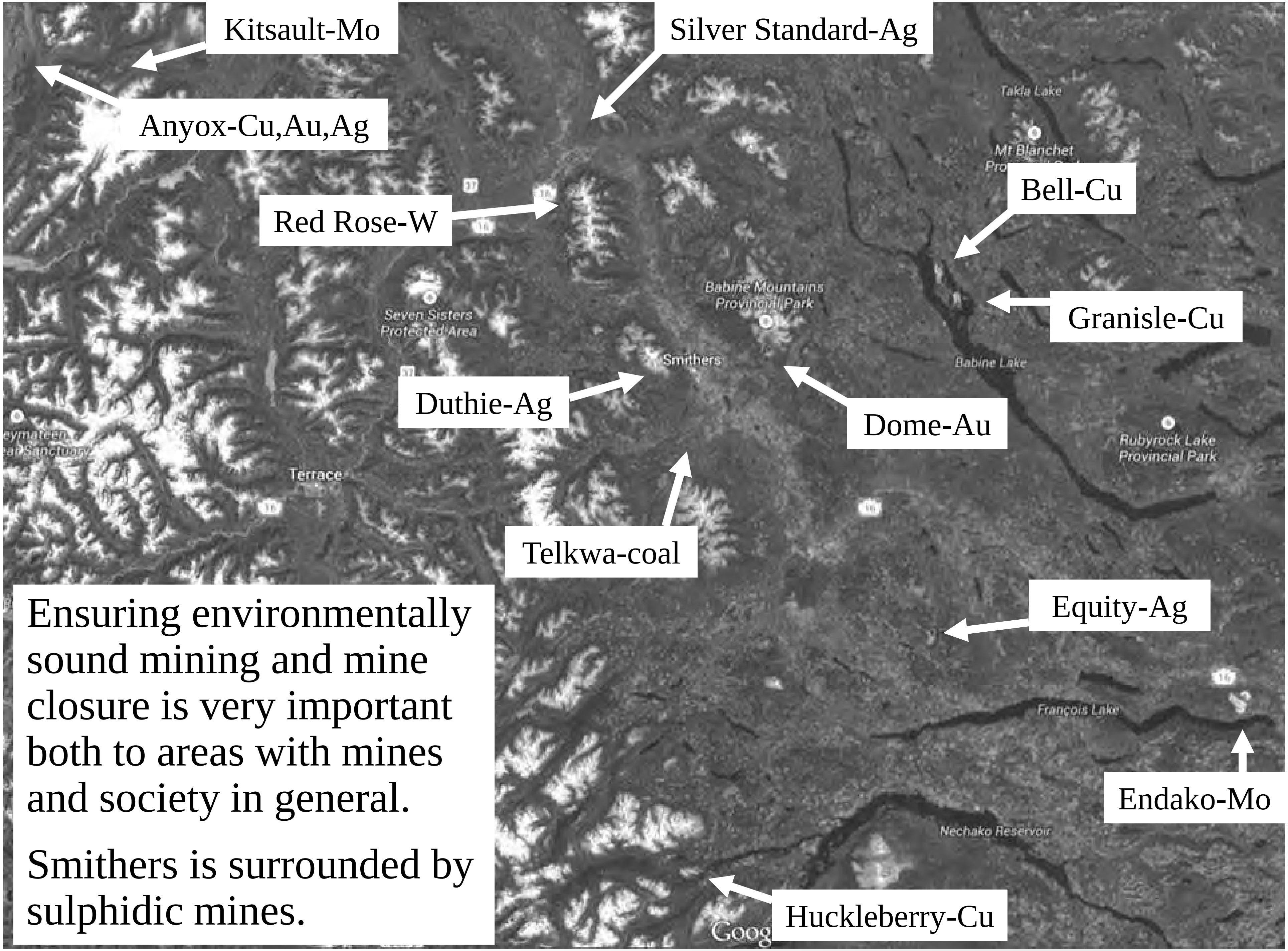
- potentially high costs and large environmental impacts;
- need to be proactive;
- many contributing processes (large info. requirements);
- many key properties in flux and difficult to measure;
- mitigation must function over long-time frame;
- limited long-term operating experience; and
- highly specialized, technical aspects of the work.

A key part of the prevention of ML/ARD impacts is having people and organizations with adequate motivation, experience, technical and site-specific understanding, and resources to conduct and manage the work.

Personnel need to invest considerable time learning site-specific details before they can make good site-specific decisions.

Although success depends on individual people, it also depends on organizational support and knowledge.

Sustaining organizational support and knowledge is a challenge when the effort and results do not help individual career advancement.

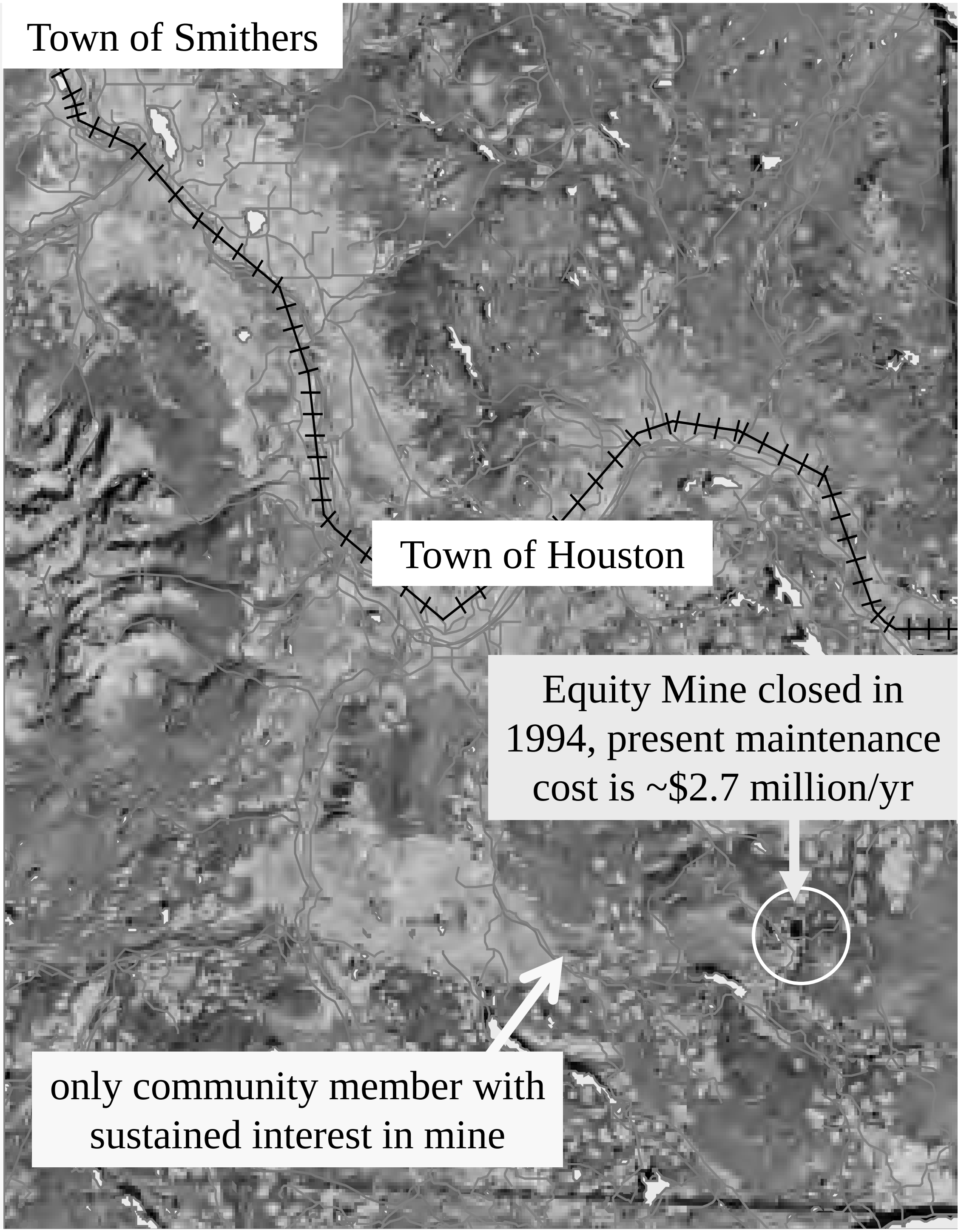


Ensuring environmentally sound mining and mine closure is very important both to areas with mines and society in general.

Smithers is surrounded by sulphidic mines.

The increasing number of mines with ML/ARD issues put an increasing strain on industry and regulatory resources.

With many other public demands and priorities and government individuals continually changing, sustained public oversight is needed to ensure government agencies have the necessary resources and motivation to do the work required in a proactive and well-informed manner.



Bio for William (Bill) A. Price

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1989-1991: Environmental Consultant

1991-2003: Senior Reviewer, Reclamation Section, BC Ministry of Energy & Mines

2003-Present: Research Scientist, CANMET-MMSL, Natural Resources Canada

Author of various guidelines for prediction and prevention of metal leaching and acid rock drainage used by various government agencies, mining companies and consultants

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