The Application of Attenuation Mechanisms in Mine-Related Environmental Assessments: The Spectrum from Conceptual Model to Numerical Implementation

Alan J. Martin, M.Sc., P.Geo., R.P.Bio.
Principal, Senior Geochemist/Biologist
Lorax Environmental Services Ltd.

LORAX ENVIRONMENTAL

The Spectrum:

- Detailed understanding of attenuation process
- Quantifiable
- Included as numerical input in model

- Conceptual understanding of attenuation process
- Not quantified in model
- Presented as “model conservatism”

- Poor understanding of attenuation process
- Not quantified in model
- Possibly presented as “model conservatism”

Numerical Implementation:

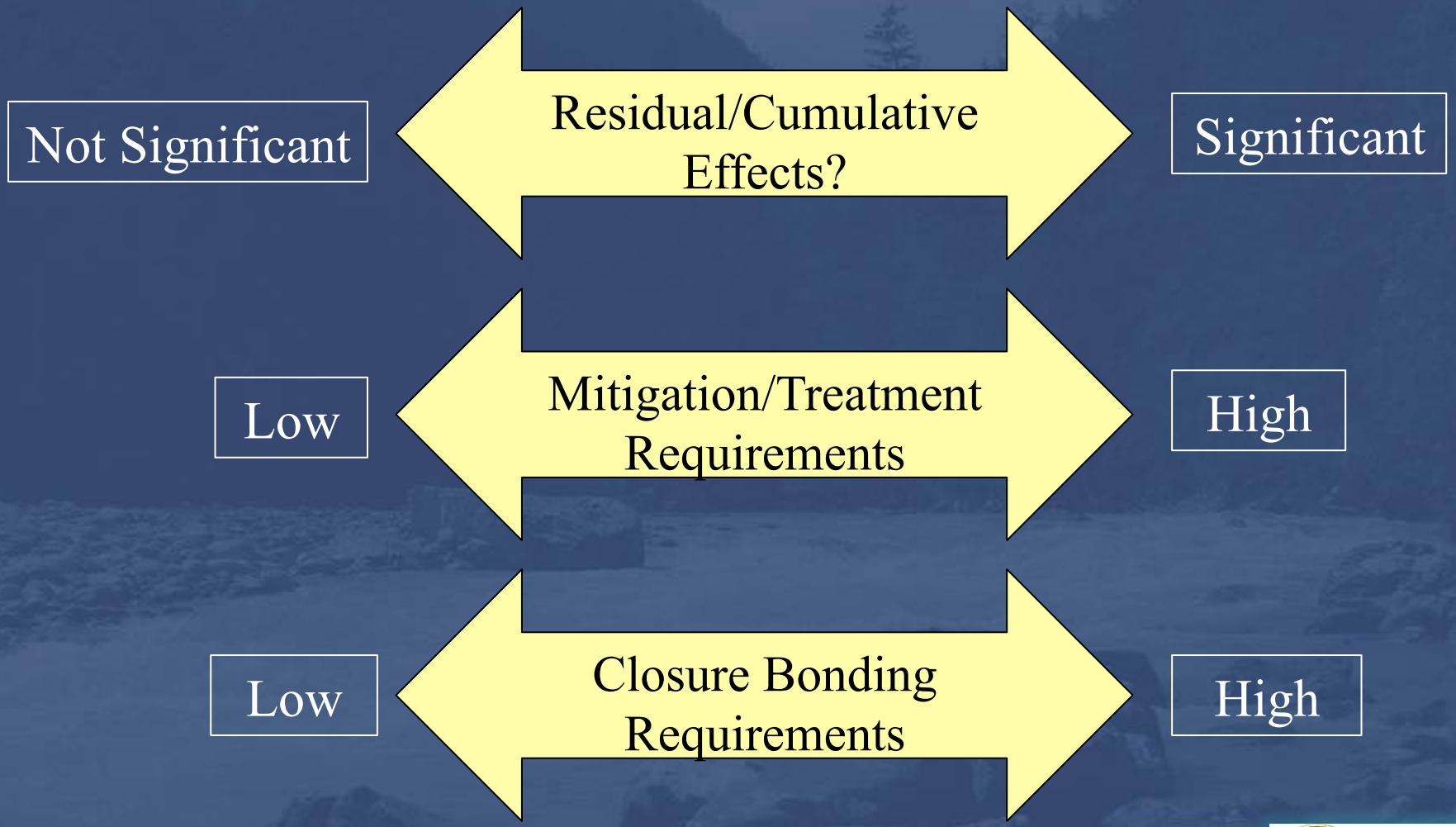
Attenuation can be expressed numerically in various ways:

1. Concentration: fixed end-member concentration that is representative of attenuation process (e.g., concentration of Se reporting from saturated waste rock).
2. Reaction rate: rate of removal (mass or concentration) per unit time.
3. Distribution coefficient (K_d): for some sorption processes, attenuation can be expressed as a constant ratio (e.g., metal sorption to Fe oxides):

$$K\downarrow d = sorbed\ metal\ concentration\ (mg/kg) / dissolved\ metal\ concentration\ (mg/L)$$

4. Reactive transport modelling: rate of removal along a flow path (mass or concentration loss per unit time and/or distance).

Implications for the Inclusion of Attenuation are Significant



LORAX ENVIRONMENTAL

Attenuation Processes are Complex

- Multiple mechanisms
  - Mineral precipitation
  - Co-precipitation
  - Adsorption
  - Oxidation/Reduction
  - Biological uptake
  - Volatilization
  - Photo-chemical processes

Processes that can vary in in time and in space.

- Complicated by:
  - Scale (bench top to facility)
  - Heterogeneity in mine systems (pathway, material properties)
  - Non-steady-state effects (kinetics, supersaturation)
  - Complexation/speciation
  - Microbial/biological processes
  - Finite processes (e.g., adsorption)

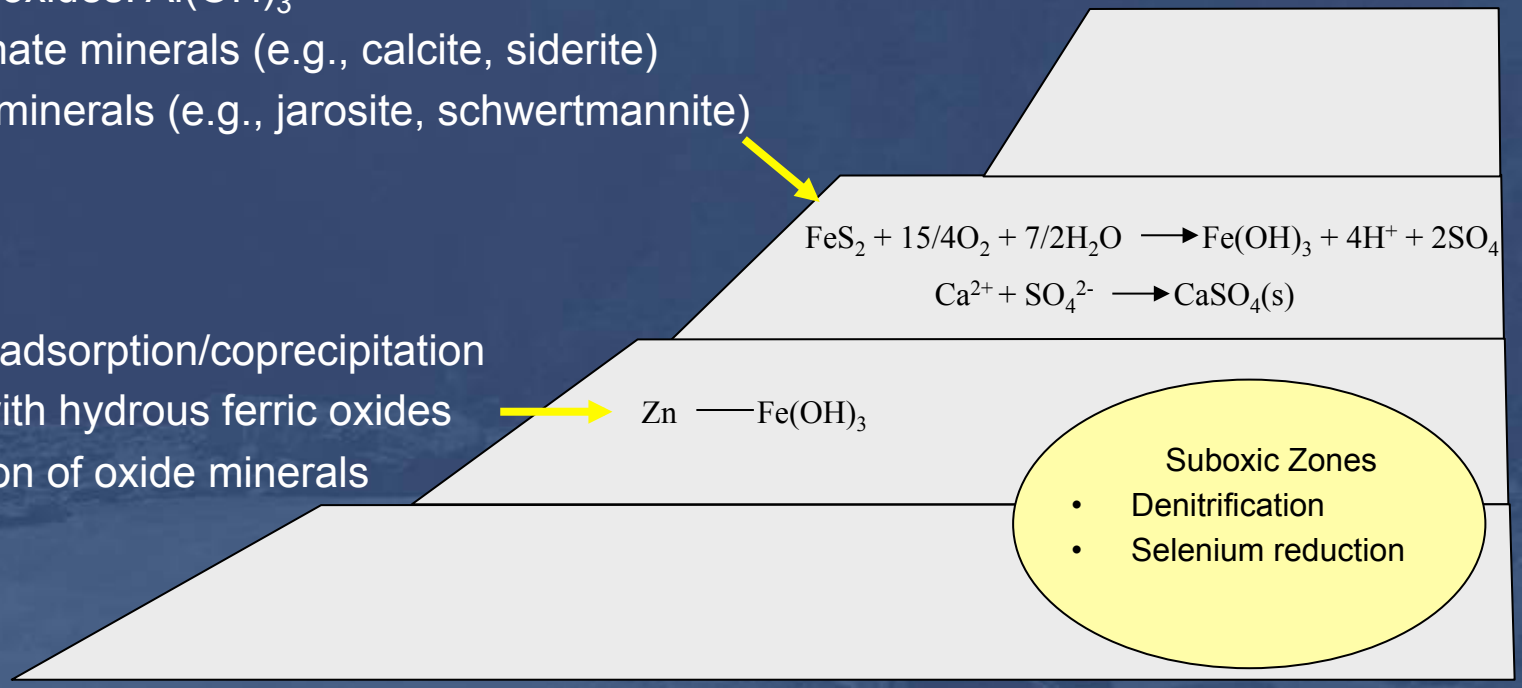
Attenuation Processes Mine Settings: Where Do They Occur?

- Source zones:
  - Mine rock
  - Pits
  - Tailings
  - Underground workings
- Pathways:
  - Seepage collection systems
  - Sedimentation ponds
  - Saturated rock fills
  - Surface water pathways
  - Groundwater pathways
- Receptors:
  - Streams
  - Lakes
  - Wetlands

Attenuation: Unsaturated Waste Rock & Tailings

- Precipitation of secondary phases associated with oxidative weathering:
  - Sulphate minerals (e.g., gypsum)
  - Fe/Mn oxides (e.g., goethite, MnO_2)
  - Al hydroxides: $Al(OH)_3$
  - Carbonate minerals (e.g., calcite, siderite)
  - Acidic minerals (e.g., jarosite, schwertmannite)

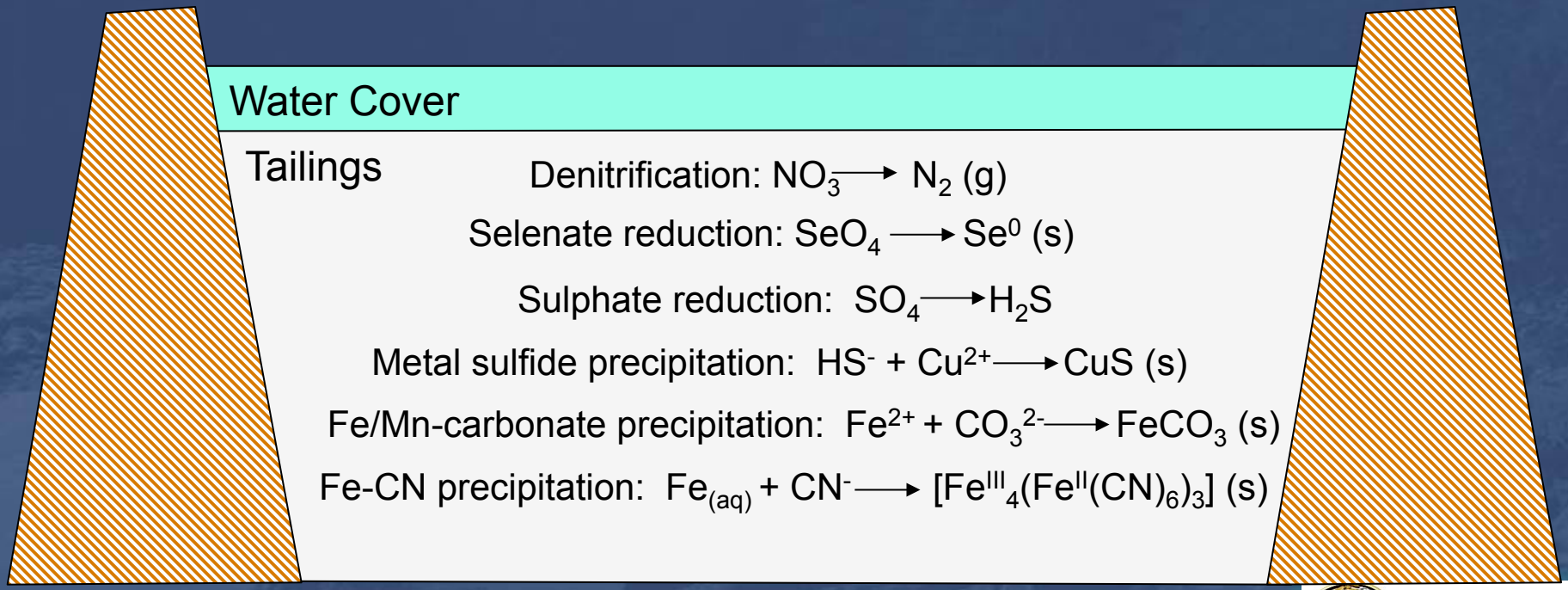
Trace element adsorption/coprecipitation
  - Sorption with hydrous ferric oxides
  - Precipitation of oxide minerals



LORAX ENVIRONMENTAL

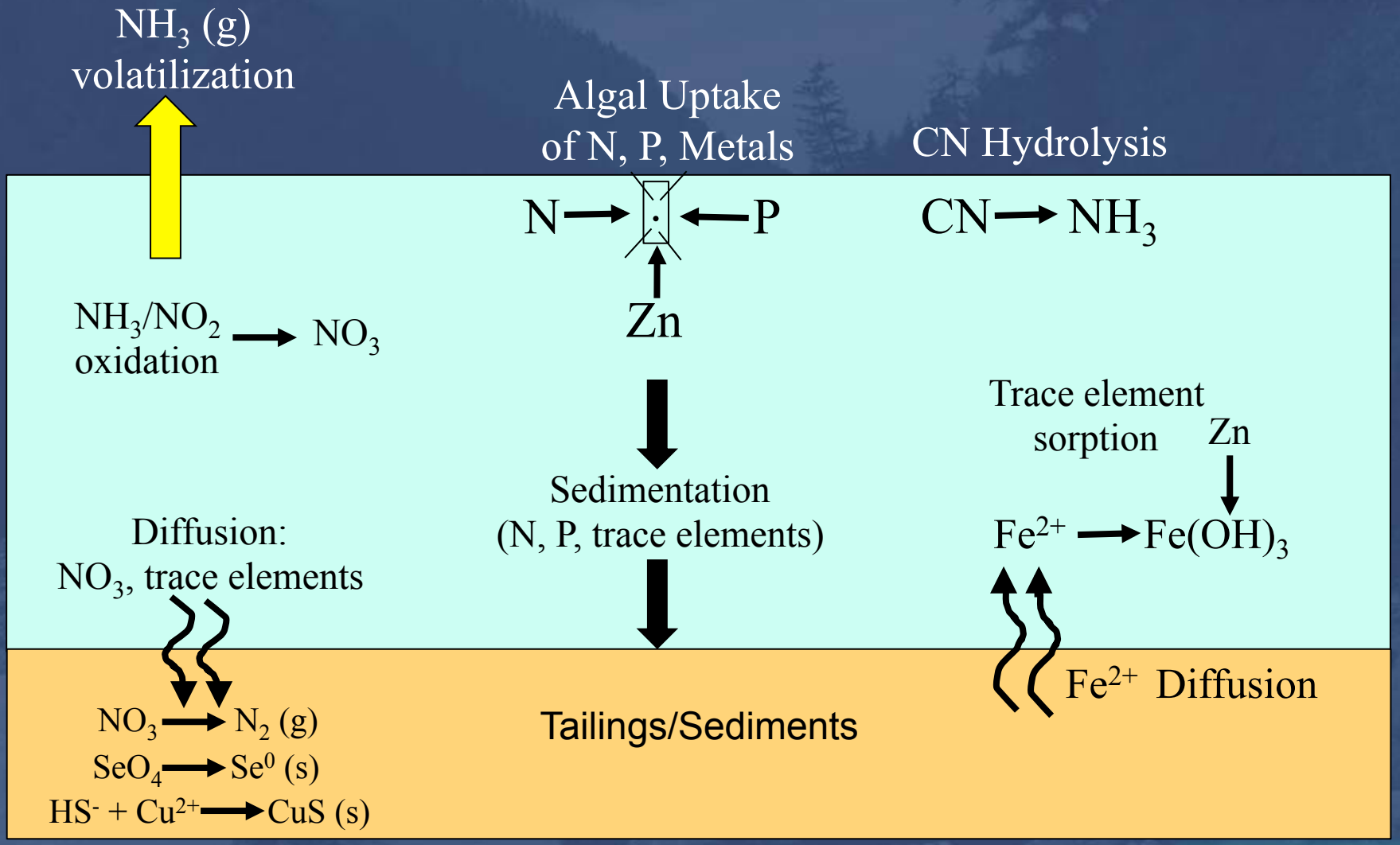
Attenuation: Saturated Waste Rock and Tailings

- Suboxic redox processes are important.
- At the base of the impoundment where tailings and waste rock are in contact with remnant vegetation and/or organic soils, there is the potential for more reducing conditions to develop.



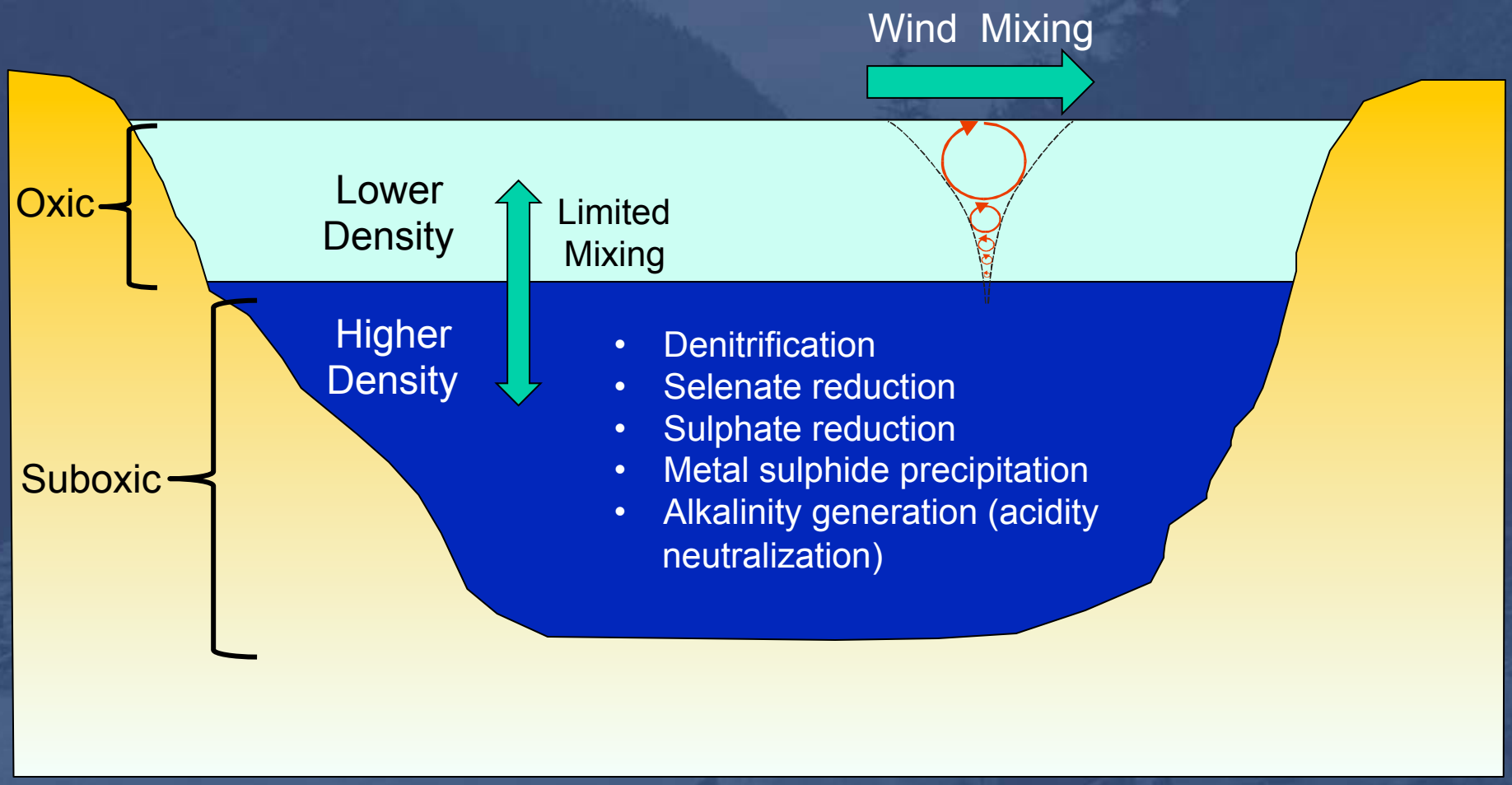
LORAX ENVIRONMENTAL

Attenuation: Tailings Ponds, Sediment Ponds & Lakes



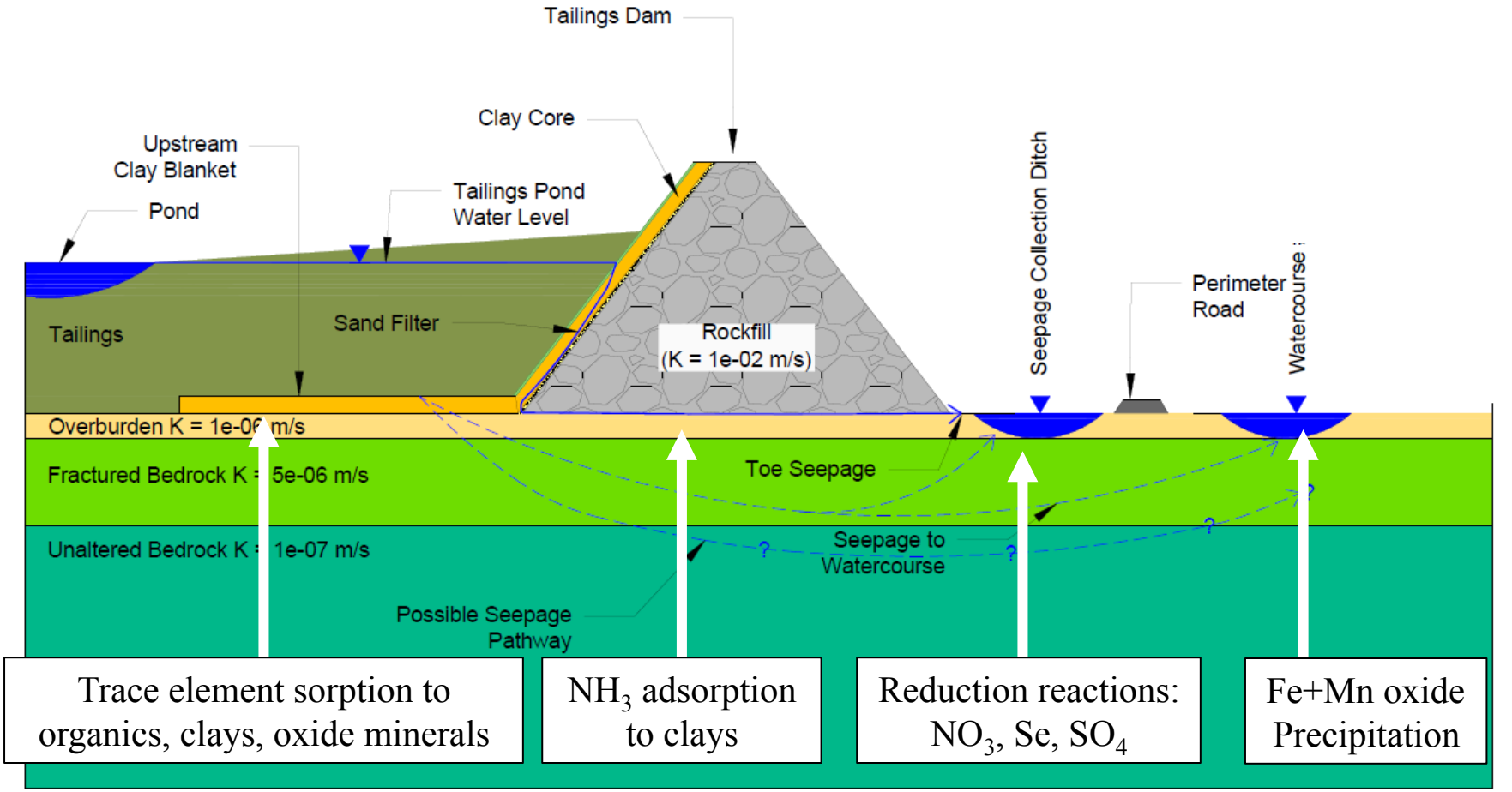
LORAX ENVIRONMENTAL

Attenuation: Stratified Pit Lakes



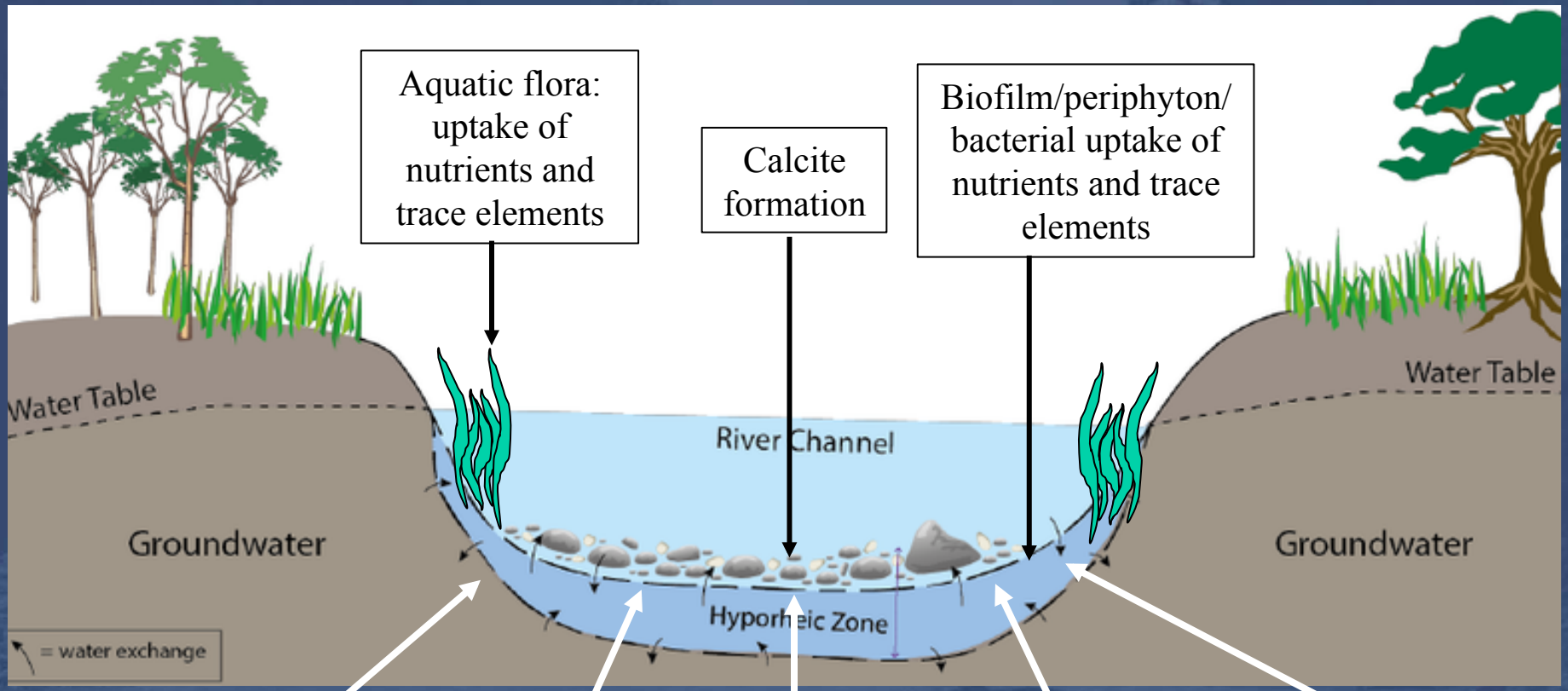
LORAX ENVIRONMENTAL

Attenuation: Subsurface Flow Pathways



LORAX ENVIRONMENTAL

Attenuation: Streams



LORAX ENVIRONMENTAL

Attenuation Process: 3 Groupings

High Confidence:
Numerical implementation warranted based on First Principles and limited site-specific information

Moderate Confidence
Numerical implementation requires some degree of site-specific evaluation

Low Confidence
Numerical implementation requires high degree of site-specific evaluation

Some Subjectivity Involved: The banjo paradigm

Maybe next year he'll learn to play to fiddle……

Attenuation Process – High Confidence

Numerical implementation warranted based on First Principles and limited site-specific information

- Particle settling (ponds, lakes)
- Phosphorus uptake: biological uptake in ponds, lakes, pit lakes.
- CN degradation (tailings ponds)
- Fe^{2+} oxidation/hydrolysis
- H_2S oxidation

} rapid oxidation kinetics

- Mineral precipitation at circum-neutral pH for certain major mineral phases (e.g., anhydrite/gypsum, barite, Fe oxides)
- Denitrification: Saturated waste rock, saturated tailings, lake sediments
- Selenium bio-reduction: saturated waste rock, saturated tailings, lake/ wetland sediments
- Lake surface waters: Trace element removal via biogenic scavenging (Cu, Cd, Ni, Zn).

Attenuation Process – Moderate Confidence

Numerical implementation requires some degree of site-specific evaluation

- Ammonia oxidation
- Nitrite oxidation
- Mn^{2+} oxidation

Variable (slow) oxidation kinetics

- Ammonia biological uptake
- Ammonia adsorption along clay-bearing groundwater pathways
- CN removal along groundwater pathways
- Metal sulphide precipitation in lake sediments, submerged tailings
- Calcite formation in ditches, streams
- Sulphate reduction: saturated tailings, lake/wetland sediments
- Alkalinity generation and acid neutralization in suboxic sediments and pit lakes.
- Co-precipitation of certain trace elements (radium with barite)

Attenuation Process – Low Confidence

Numerical implementation requires high degree of site-specific evaluation

- Metal attenuation in low-pH systems (e.g., acidic sulfate minerals)
- Trace element adsorption/co-precipitation along groundwater flow paths
- Stream attenuation processes: trace element adsorption, biological uptake, metal co-precipitation with secondary minerals
- Sulphate reduction along groundwater pathways
- Sulphate reduction in stratified pit lakes
- Metal sulphide precipitation in stratified pit lakes
- Volatilization from surface water systems (e.g., Se, Hg)

What are the tools? – Scientific Method

- Environmental baseline investigations:
  - Geology, Hydrogeology, WQ, Hydrology, etc.
- Kinetic test work (lab scale, pilot scale, field scale)
- Adsorption testwork
- Mineralogy: microscopy, extractions, etc.
- Natural analogues
- Mine site analogues
- Geochemical modelling
- Reactive transport modelling

Pre-Mining

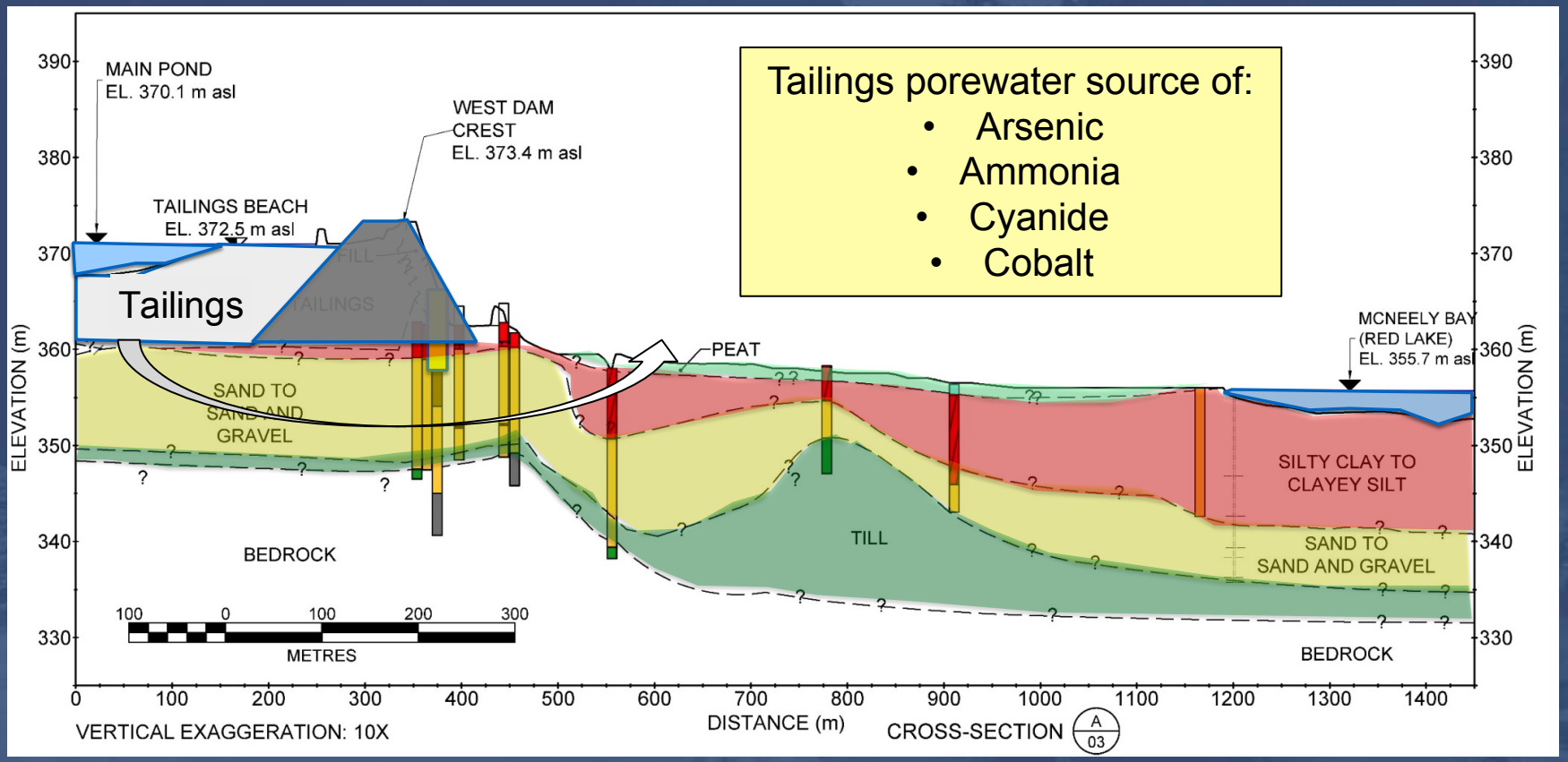
- Operational monitoring data (site specific)
  - Waste rock seepage/porewater
  - Tailings seepage/porewater
  - Groundwater quality and pathways
  - Surface water quality and pathways
  - Model refinement

Operations

A Cautionary Warning:
Cobalt case study - Red Lake Gold Mines

LORAX ENVIRONMENTAL

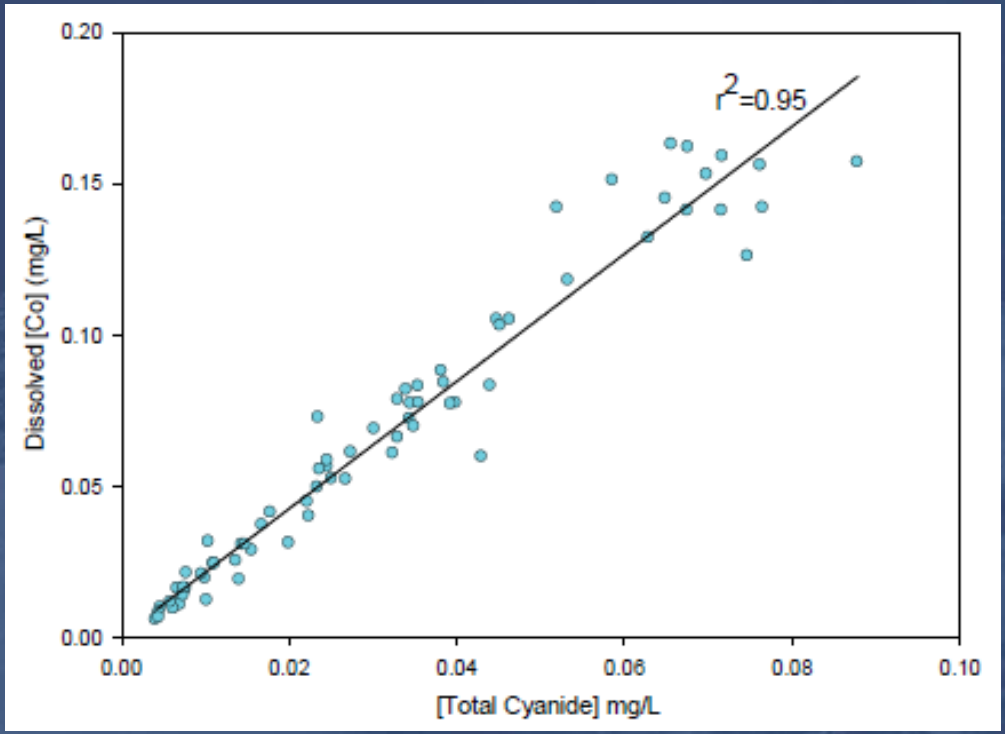
A Cautionary Warning:
Cobalt case study - Red Lake Gold Mines



LORAX ENVIRONMENTAL

A Cautionary Warning: Cobalt case study - Red Lake Gold Mines

- Arsenic, ammonia and cyanide show pronounced attenuation along groundwater flow paths (interaction with peat and clayey-till).
- In contrast, cobalt shows conservative behaviour in groundwater.
- In bench-scale permeable reactive barrier (PRB) testwork, cobalt removal is limited, even in presence of abundant free sulphide.



- Unpredictable behaivour of Co can be explained by its presence as strong CN-complexes (as inferred by Co speciation testwork).

LORAX ENVIRONMENTAL

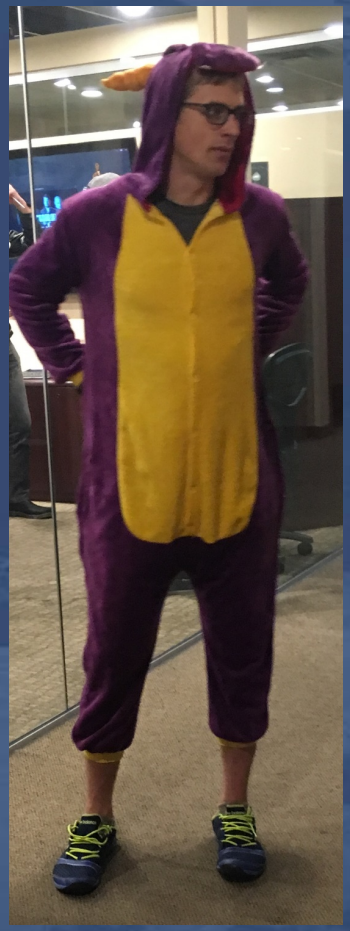
Summary

- Attenuation mechanisms are varied and complex.
- Conceptual models represent an effective way to illustrate pathways and attenuation processes.
- The inclusion of numerical attenuation factors in “base case” water quality prediction models will be highly parameter specific and site-specific.
- For many attenuation processes, a high-level of site-specific evaluation will be required to permit numerical application.
- Expect the unexpected.

Acknowledgements

John Dockrey

Elliott Skierszkan



Justin Stockwell

LORAX ENVIRONMENTAL

Thank You!