The Role of Applied Geochemistry in the Mine-Life Cycle

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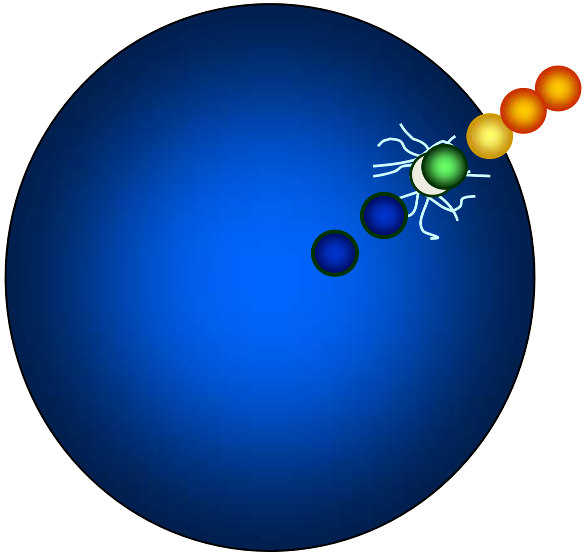
Location: CSM, Colorado

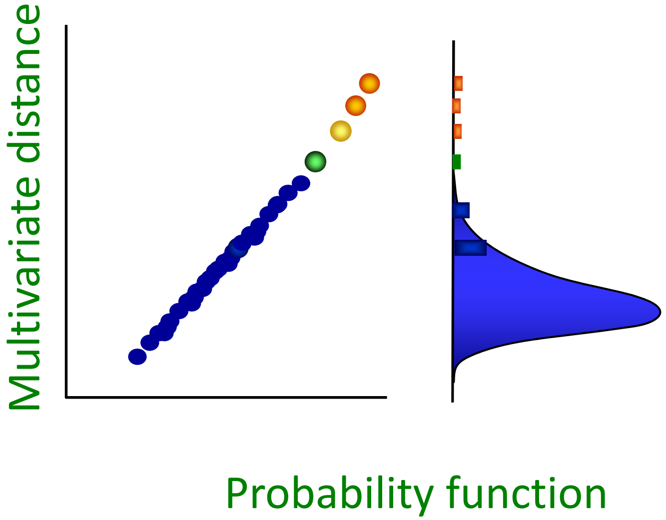
Introduction

- Why geochemistry?
  - –Quantify concentration of target elements
  - –Identify anomalous concentrations of associated elements to the target
  - –Determine control chemical characteristics have on physical properties
  - –Trouble shoot problems before or as they occur
  - –Modify mine plan/process or review regulatory procedures
- Where does this fit in?
  - –Exploration
  - –Mine development
  - –Mine operation
  - –Closure & Reclamation

Defining Anomalies

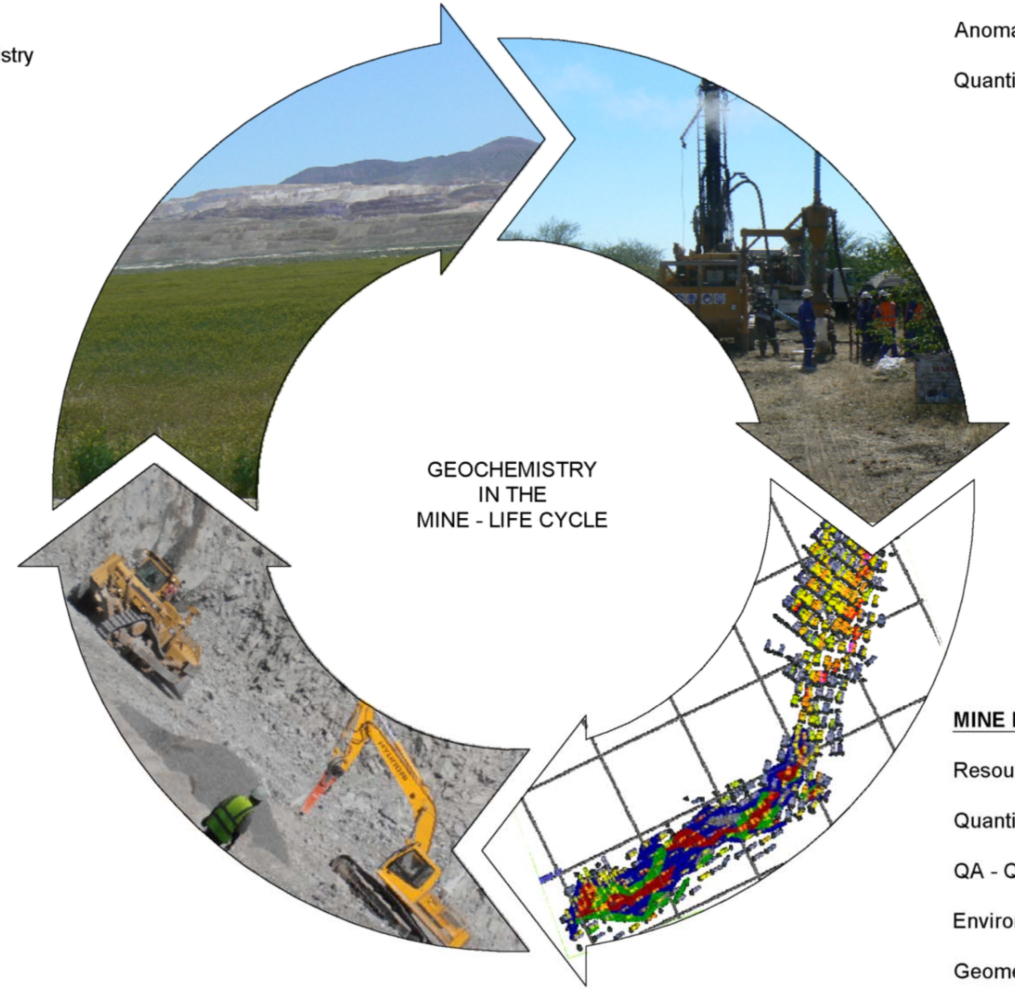
Traditional approach – satellite spotting





Objective – detect samples whose geochemistry appears "anomalous"

The Mine Life Cycle



GEOCHEMISTRY
IN THE
MINE - LIFE CYCLE

CLOSURE

Prediction of chemical stability of mining areas and waste impoundments

Prediction of future hydrogeochemistry

Waste water management

Long term reclamation

Monitoring

EXPLORATION

QA - QC

Anomaly definition

Quantification of concentration

MINE DEVELOPMENT

Resource Estimation

Quantification

QA - QC

Environmental Assessment

Geometallurgy

OPERATIONAL SUPPORT

QA - QC

Chemical stability of rocks

Hydrogeochemical monitoring

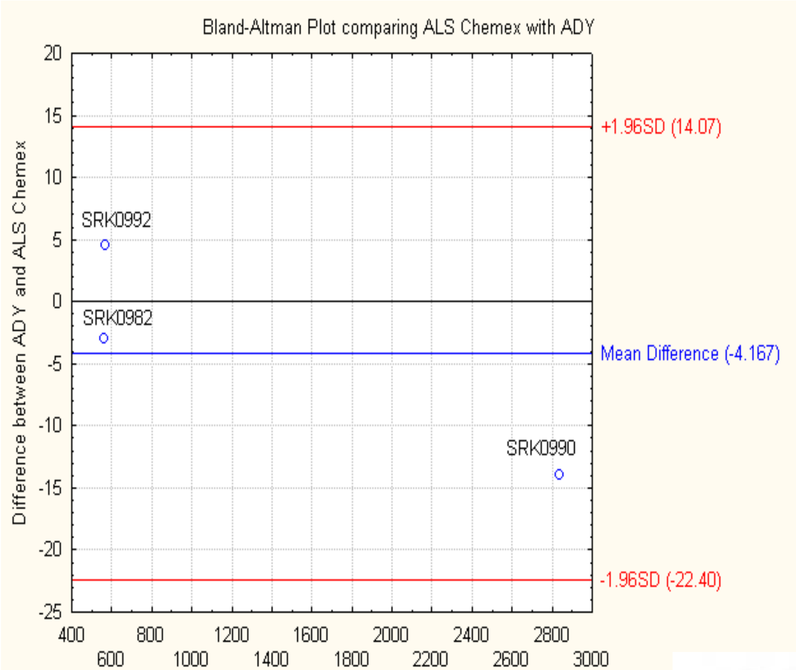
Geometallurgy

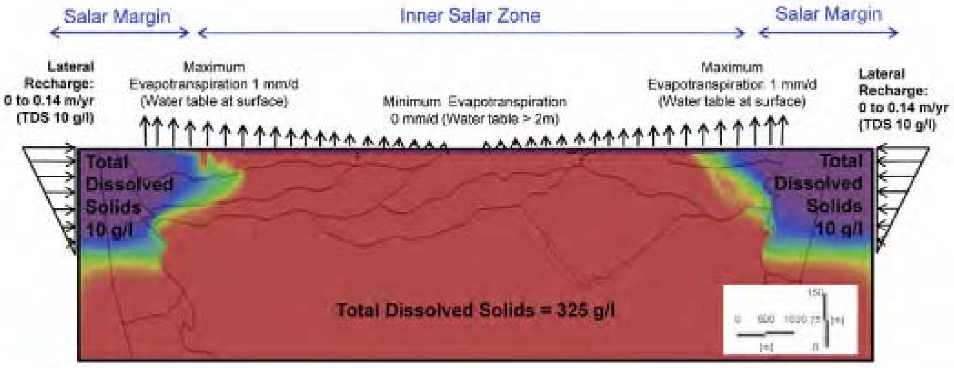
Waste Management

QA-QC

- Essential role of a geochemist, verification of the numbers
- Ensure samples collected are representative
- Ensure the numbers obtained have consistency, precision & repeatability
- Data management
- External verification: Common commodities eg gold, copper, nickel, iron obtain international standards
- New commodity types or data collection methods need to generate site specific standards

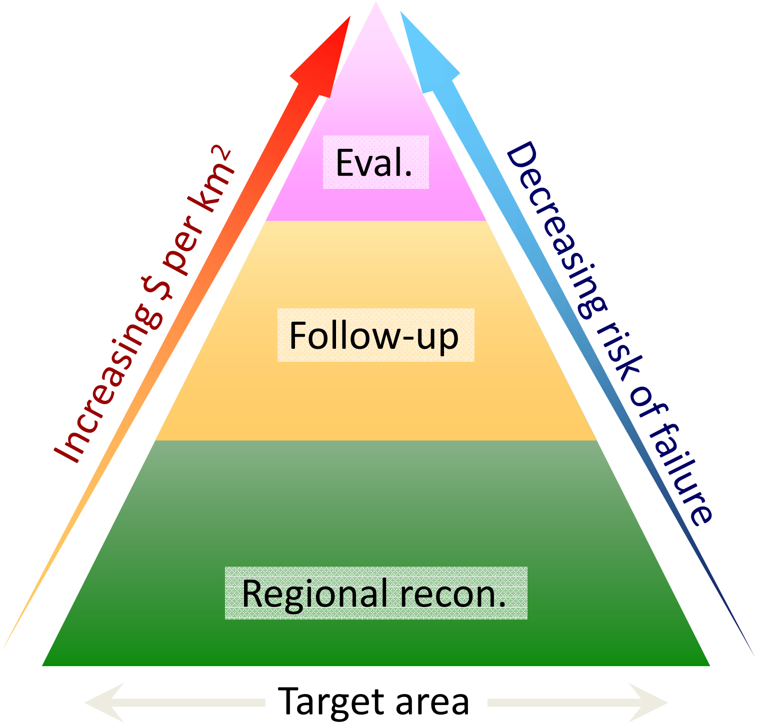
Lithium Brines





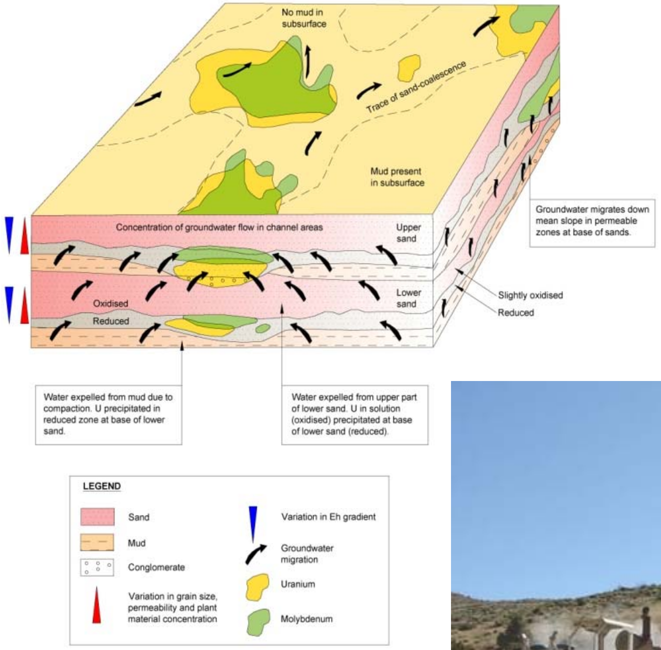
Objectives of Exploration Geochemistry

- The ultimate objective of geochemical exploration is to separate barren from mineralized rock/regolith
- Early stages of exploration need to rapidly identify areas of potential
- Empirical approaches have some gains but improved understanding of geochemical processes will produce
  - more efficient exploration program design
  - faster isolation and evaluation of prospective ground

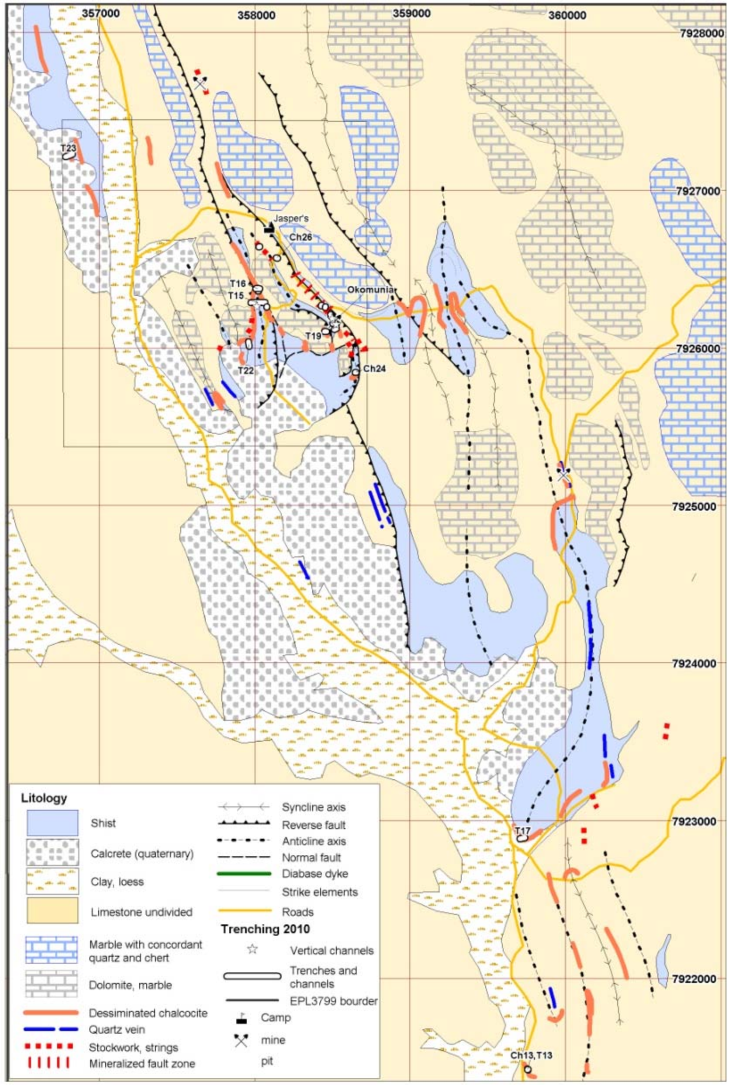


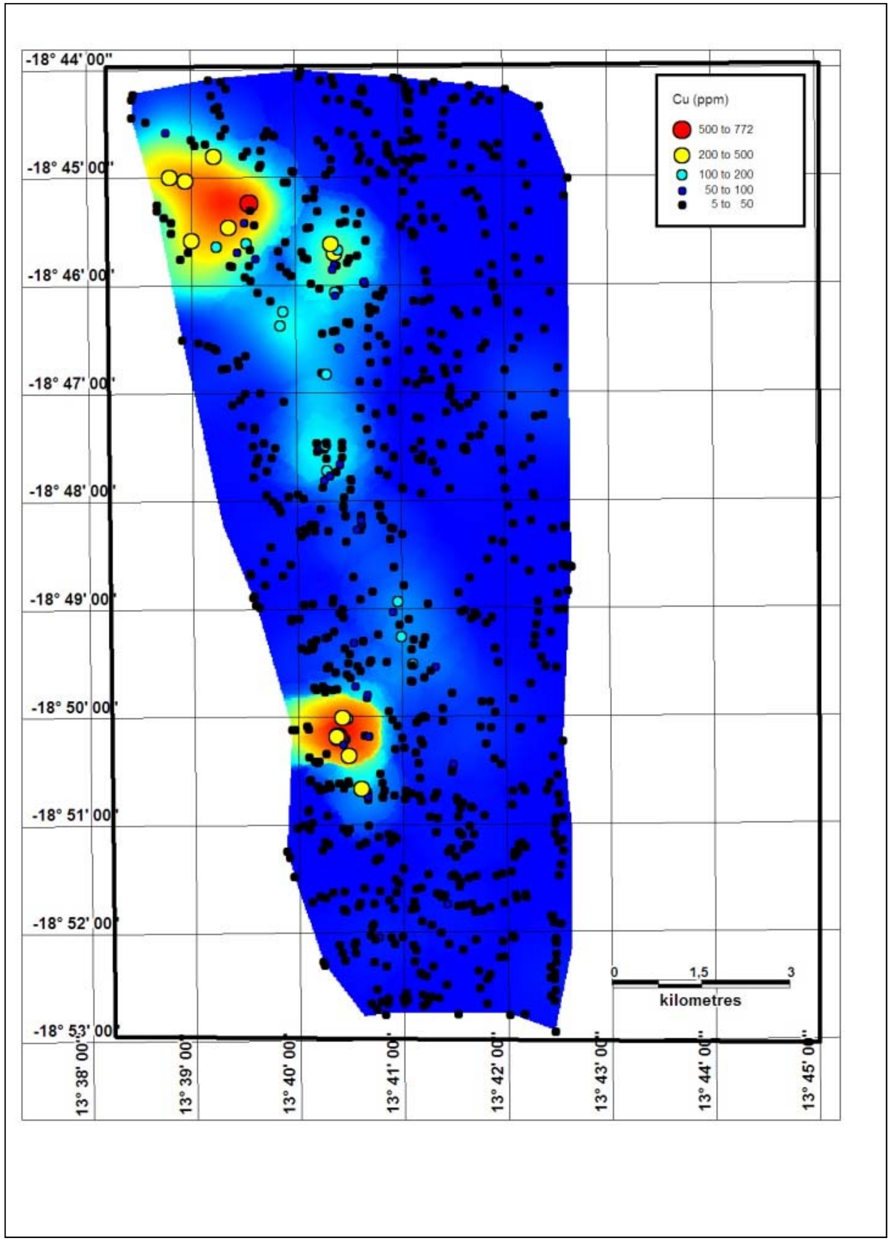
Advances in Exploration Geochemistry

- Terrain modelling
- Exploration models
- Geochemical dispersion models
- Deep/transported material
- Sampling media
- Sample analysis
- Field/Rapid analysis
- Regional mapping
- Data modelling/ manipulation



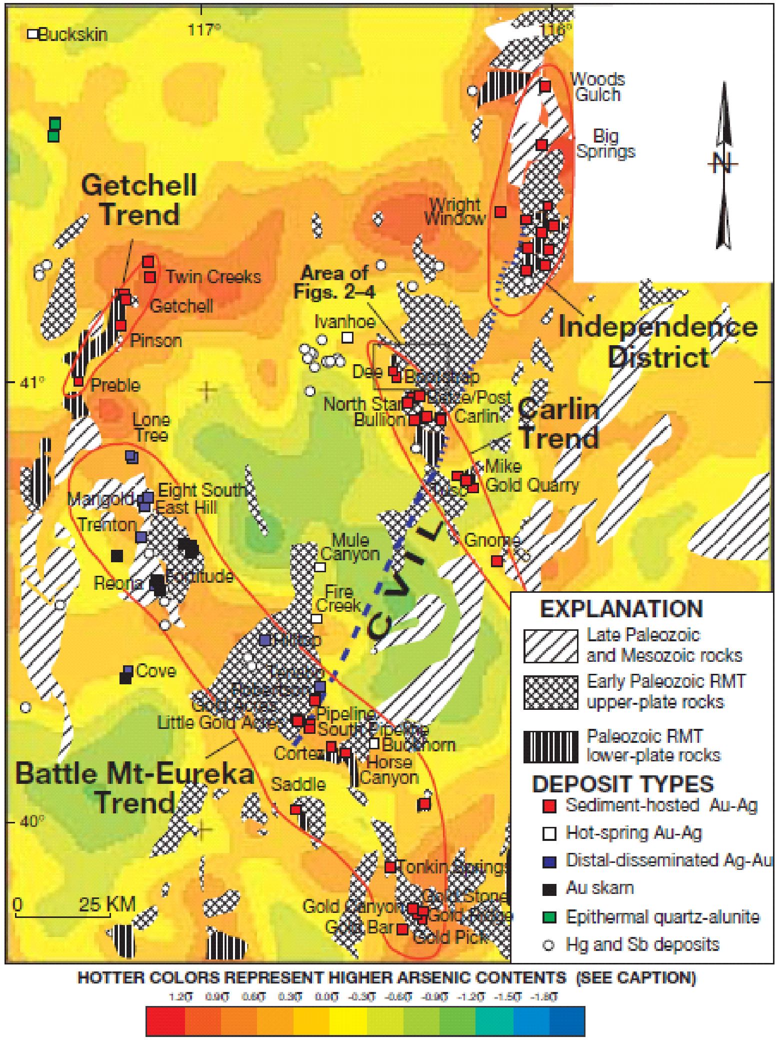
Portable Analysis





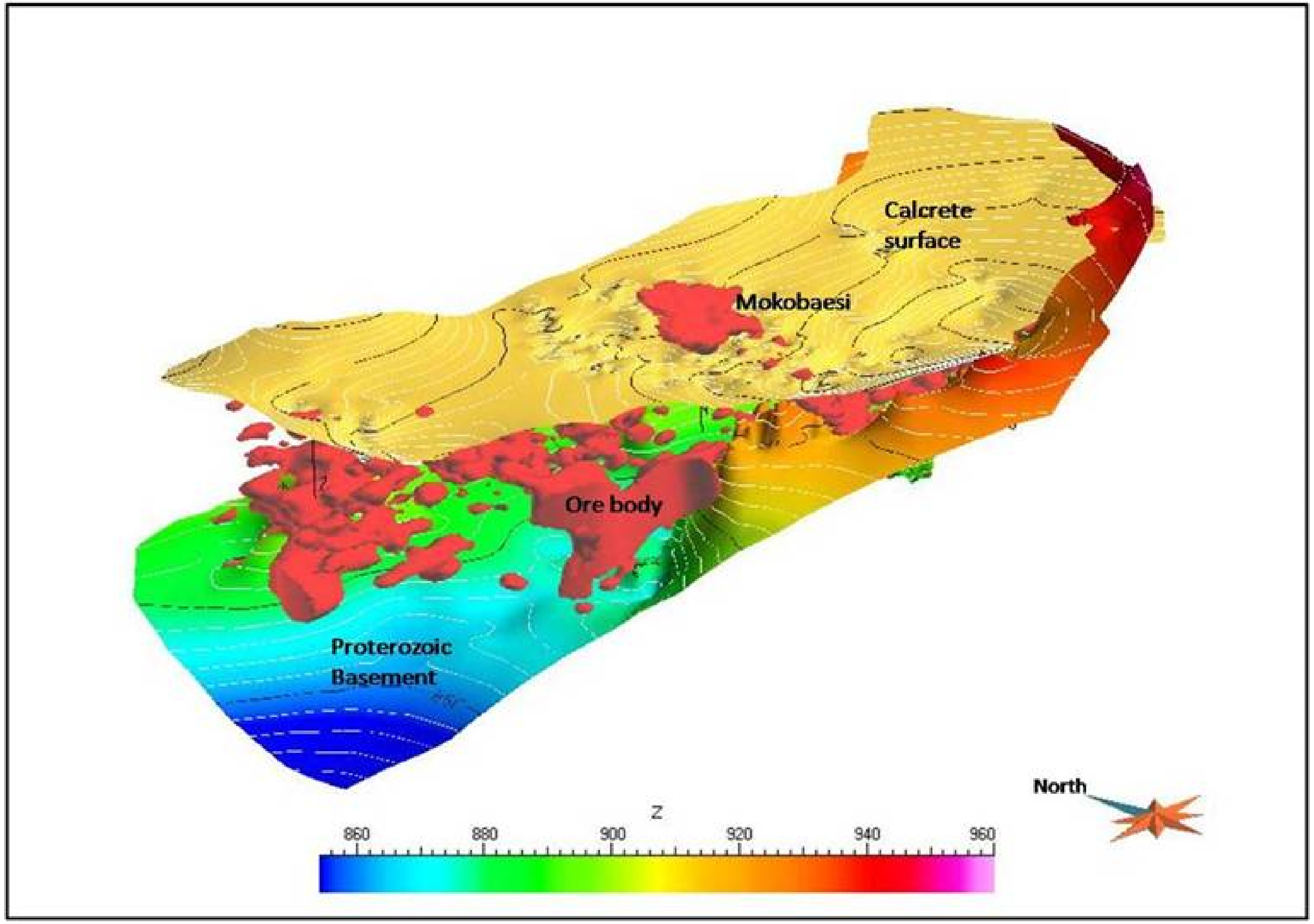
Terrane models: Chalcophile corridor

- Chalcophile corridor
  - *"Existence of regional geochemical trends of chalcophile and associated elements"* Smith et al., 1989
- Several exist in north central Nevada
  - Carlin trend
  - Battle Mountain
  - Getchell
  - Independence district
  - Bald Mountain

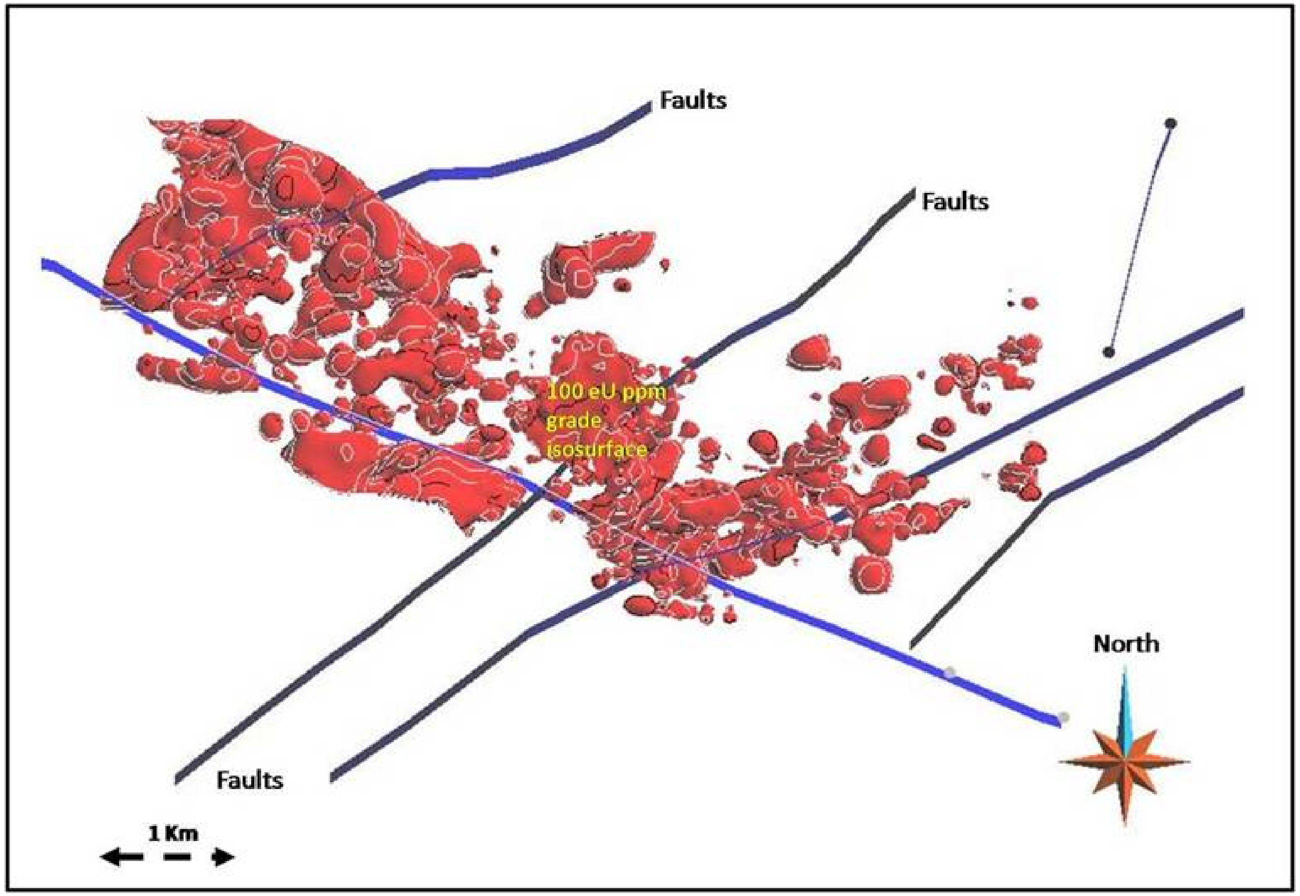


Theodore et al. 2003

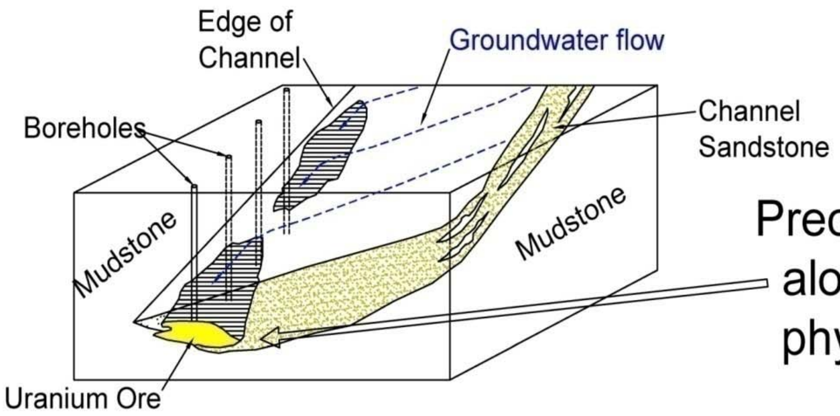
Geochemical modelling of deposits



Using Geochemistry to understand Ore Genesis

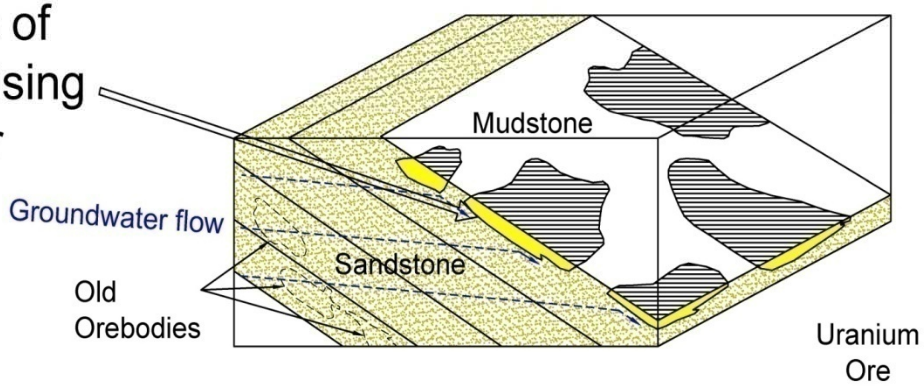


Interpretation of Geochemical trends

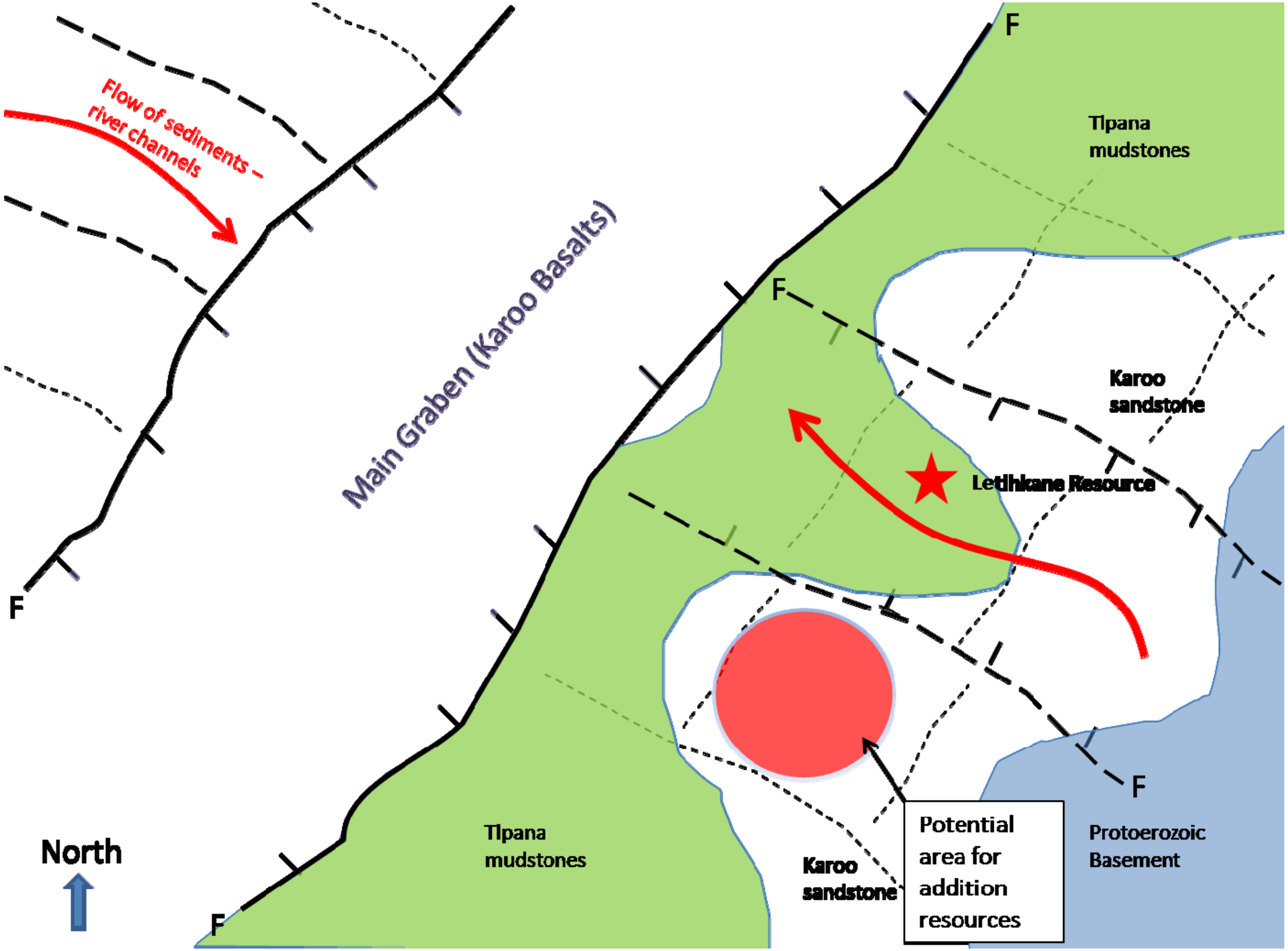


Precipitation of uranium along structures onto physiochemical traps

Remobilisation of uranium by oxidising groundwater

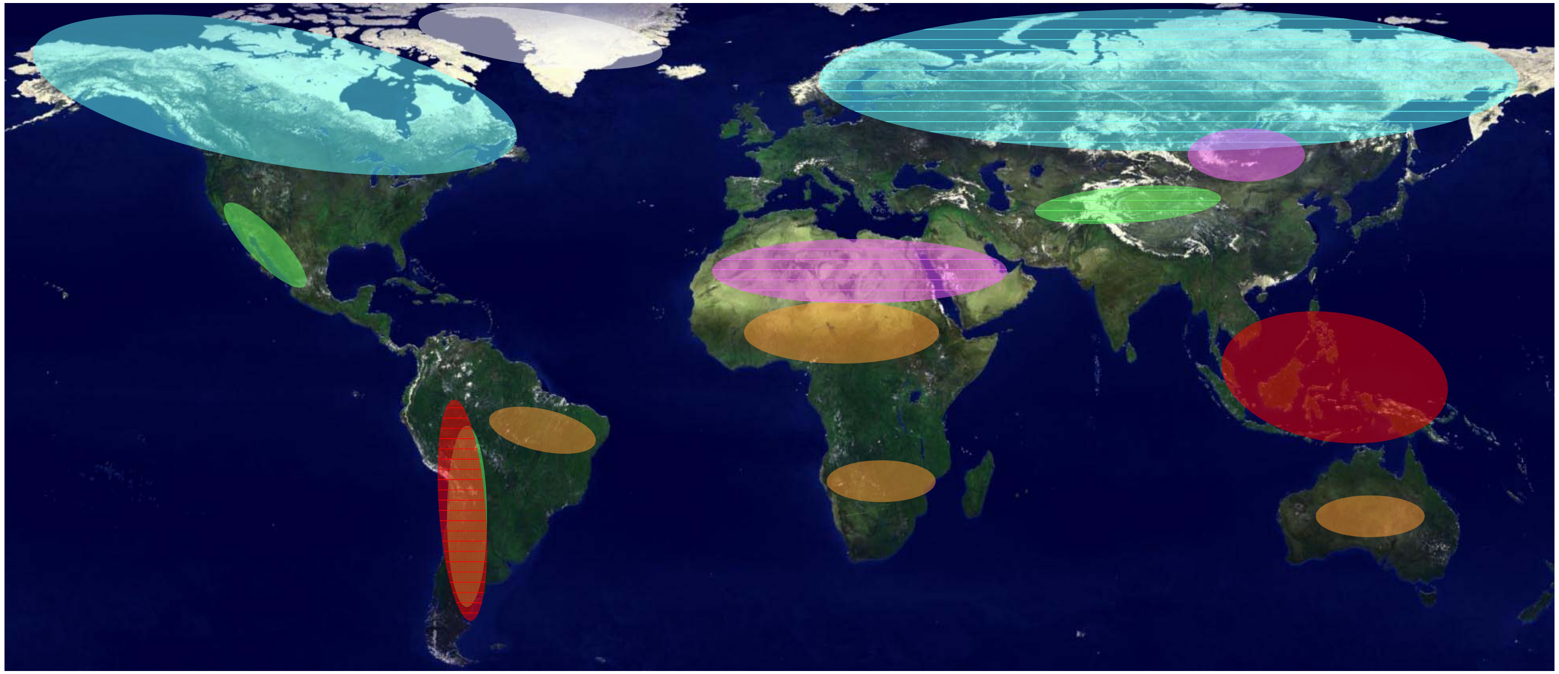


Predicting new orebodies



Potential area for addition resources

Exploration under cover



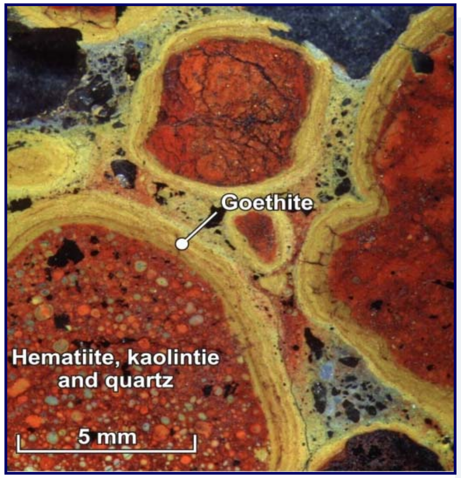
- 🟦 Glacial deposits
- 🟩 Thick gravel and scree deposits
- 🟧 Thick alluvium or colluvium + deep weathering
- 🟪 Aeolian deposits
- 🟥 Volcanic ash
- ⬜ Ice

Sample selection

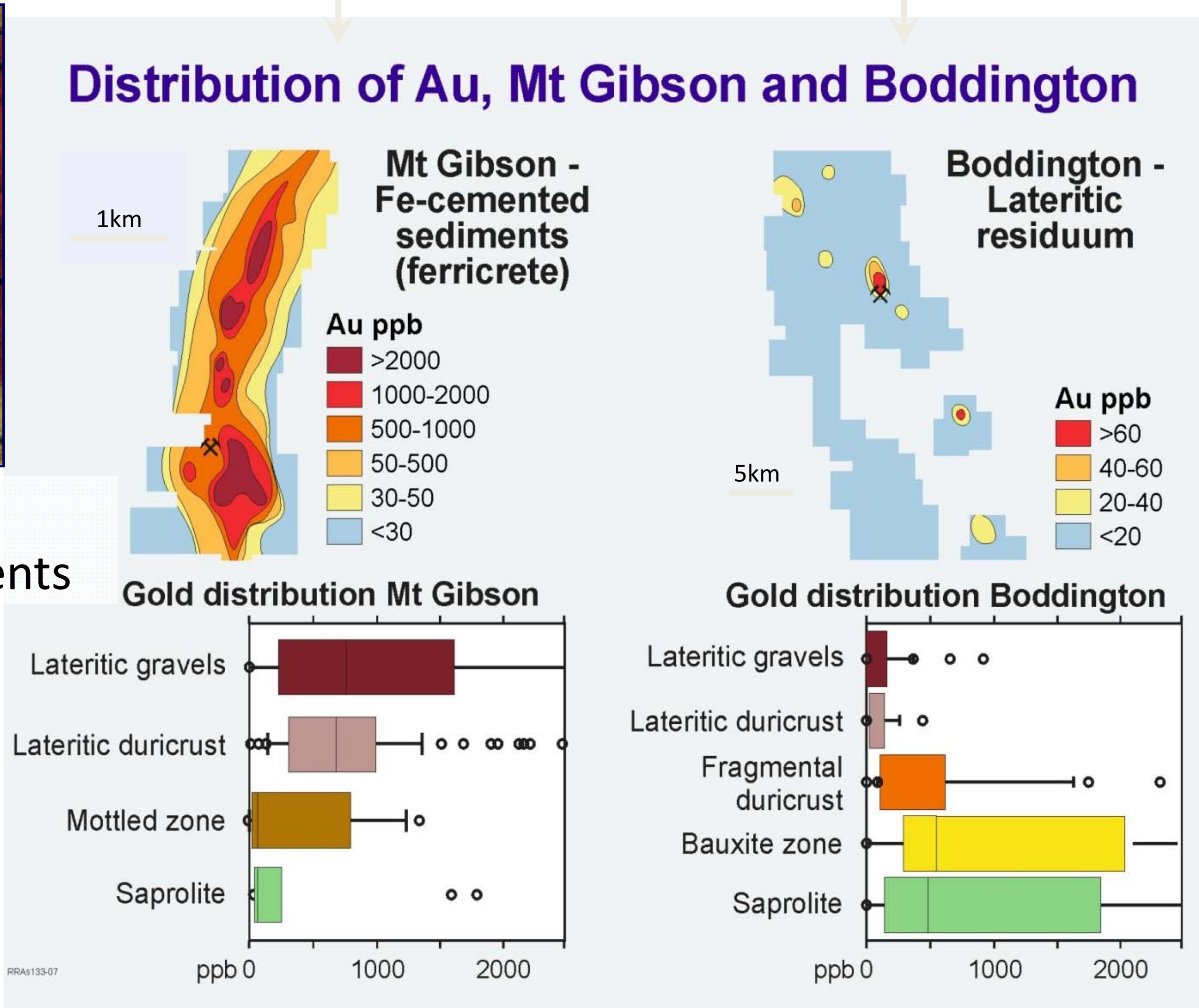
Optimum for

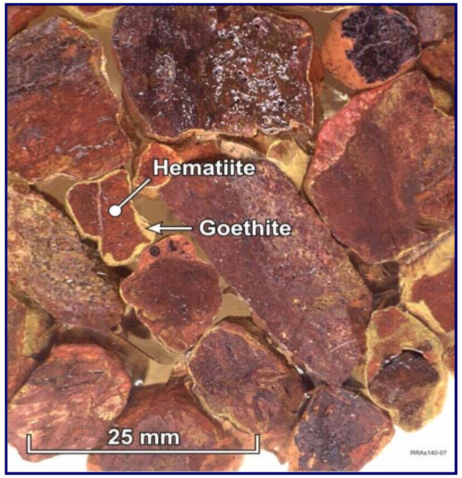
Regional scale

Local scale



Pisoliths from Fe-cemented sediments

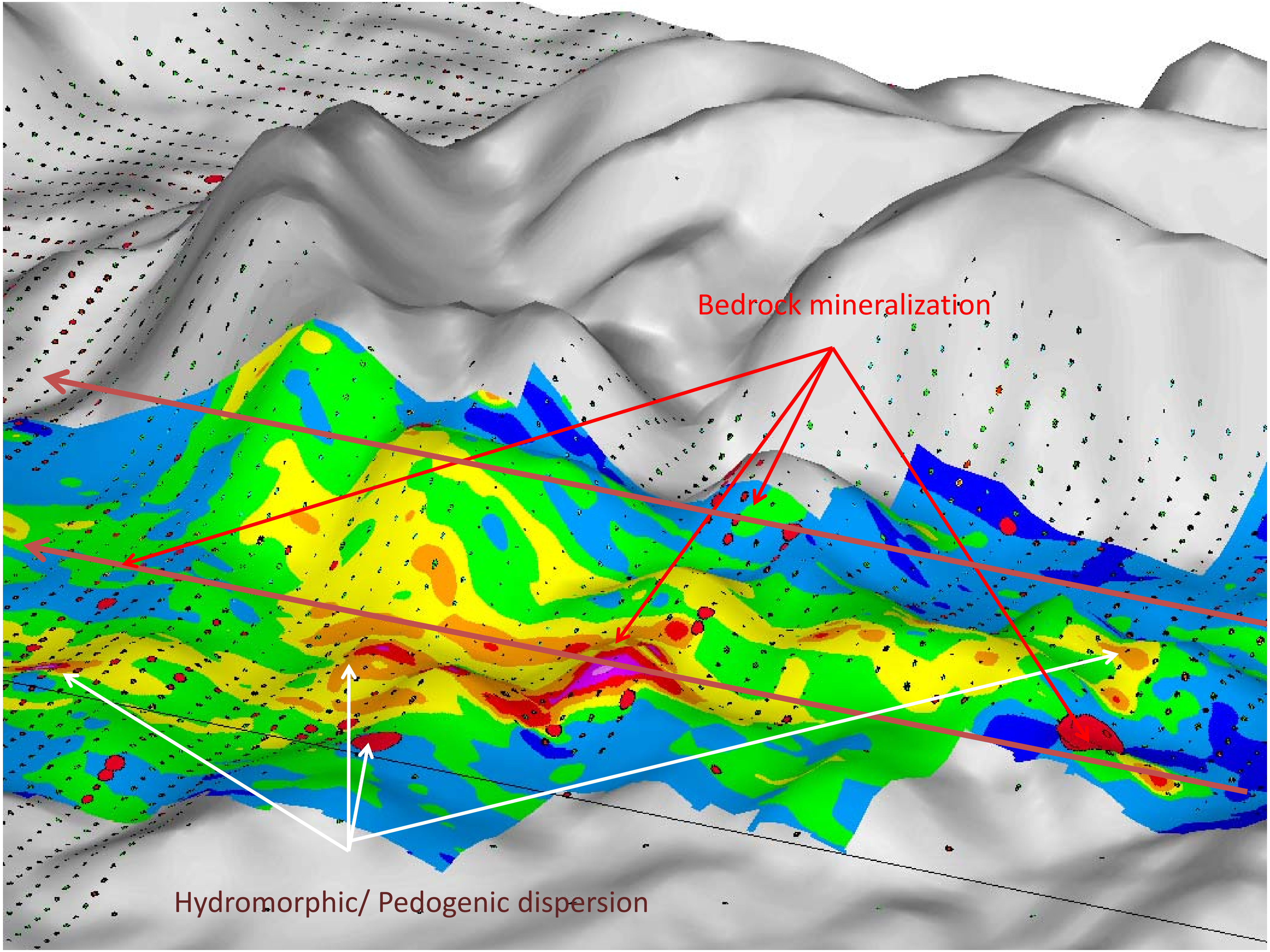




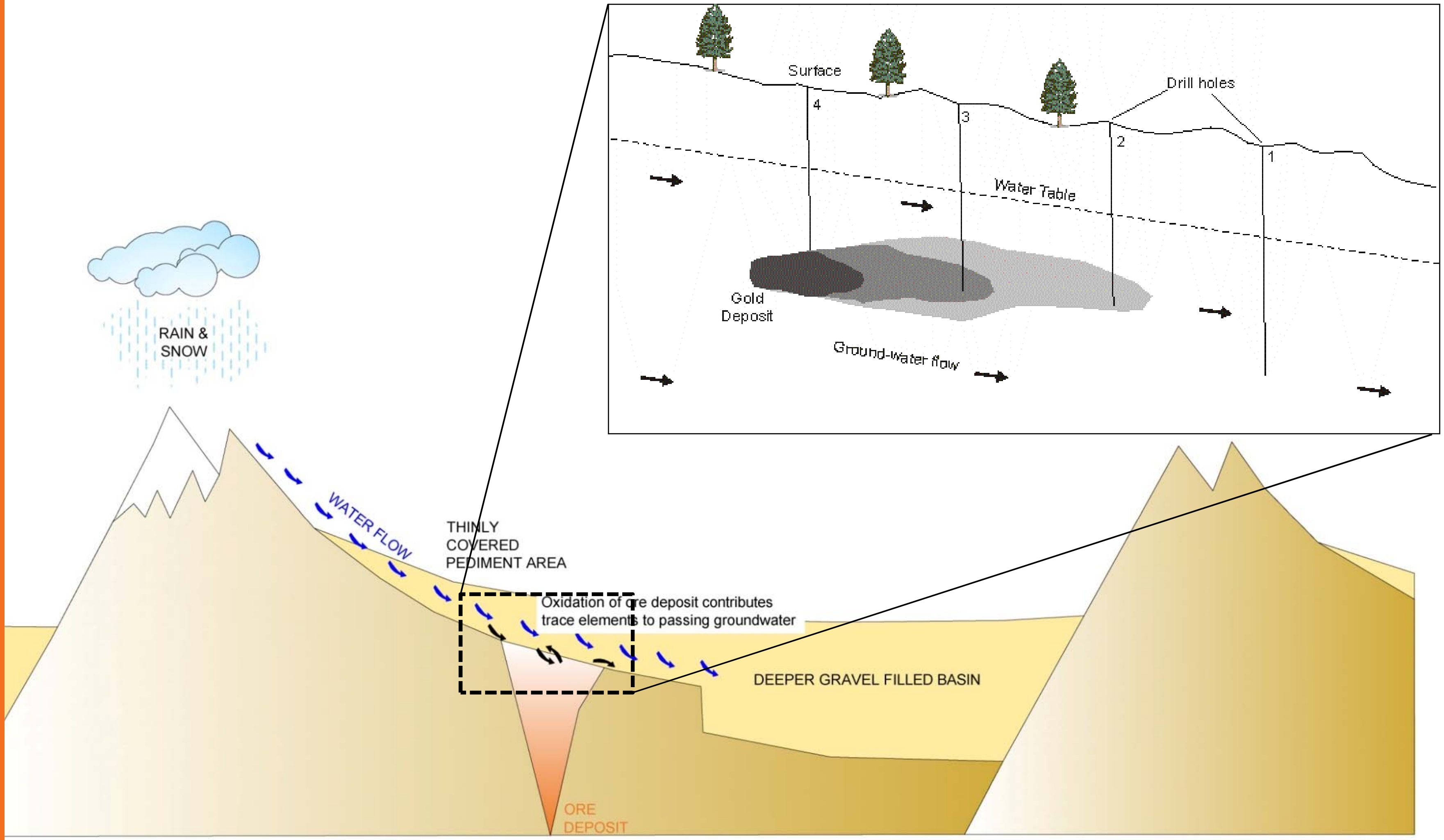
Pisoliths from lateritic residuum

Significant distribution variation between regolith type ⇒ avoid mixing

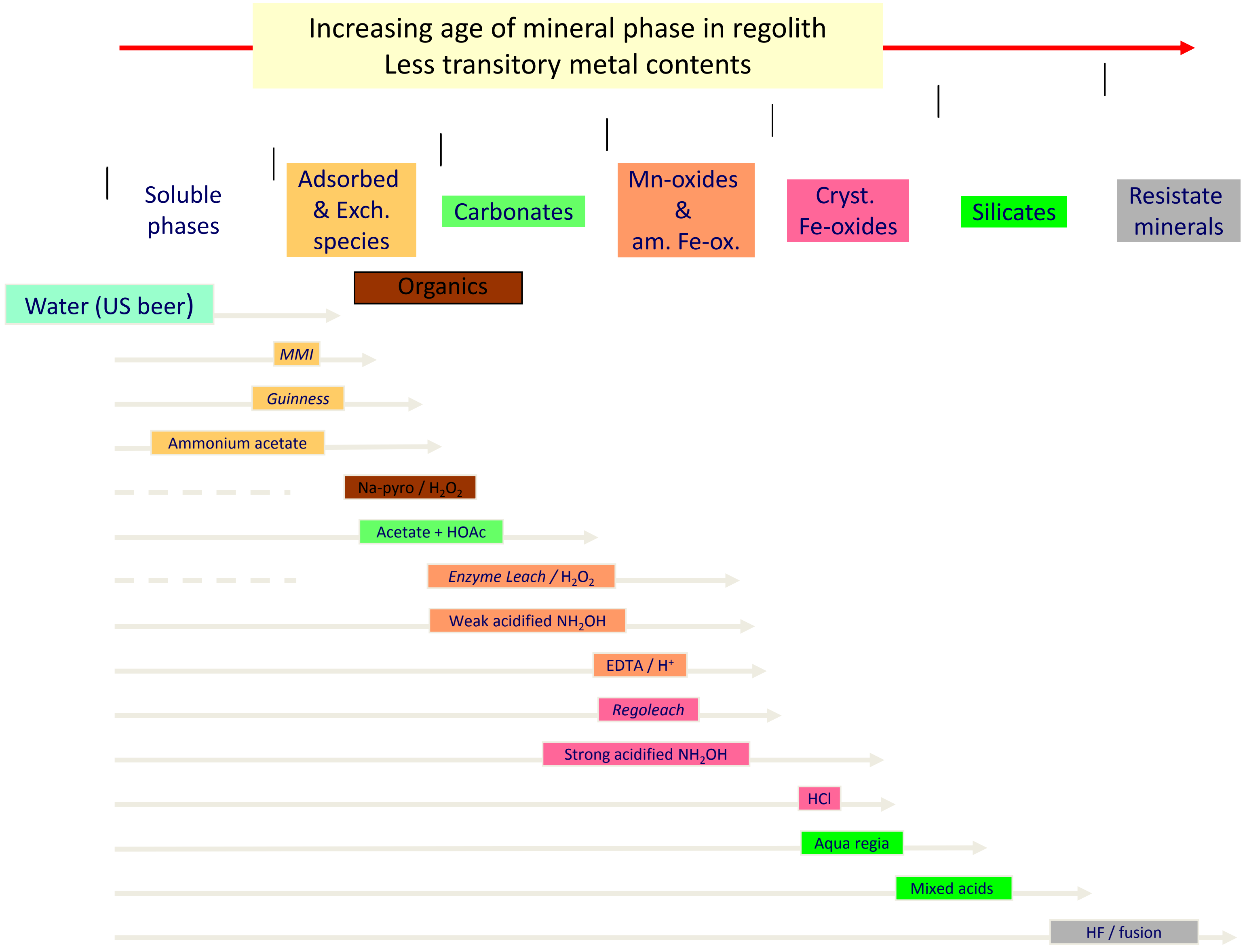
Butt et al. 1992; Pillans, 2005


Bedrock mineralization
Hydromorphic/ Pedogenic dispersion

Hydrogeochemical exploration



Partial or Selective Extractions



Increasing age of mineral phase in regolith
Less transitory metal contents

Soluble phases

Adsorbed & Exch. species

Carbonates

Mn-oxides & am. Fe-ox.

Cryst. Fe-oxides

Silicates

Resistate minerals

Organics

Water (US beer)

MMI

Guinness

Ammonium acetate

Na-pyro / H_2O_2

Acetate + HOAc

Enzyme Leach / H_2O_2

Weak acidified NH_2OH

EDTA / H^+

Regoleach

Strong acidified NH_2OH

HCl

Aqua regia

Mixed acids

HF / fusion

(based on Gray, 1999)

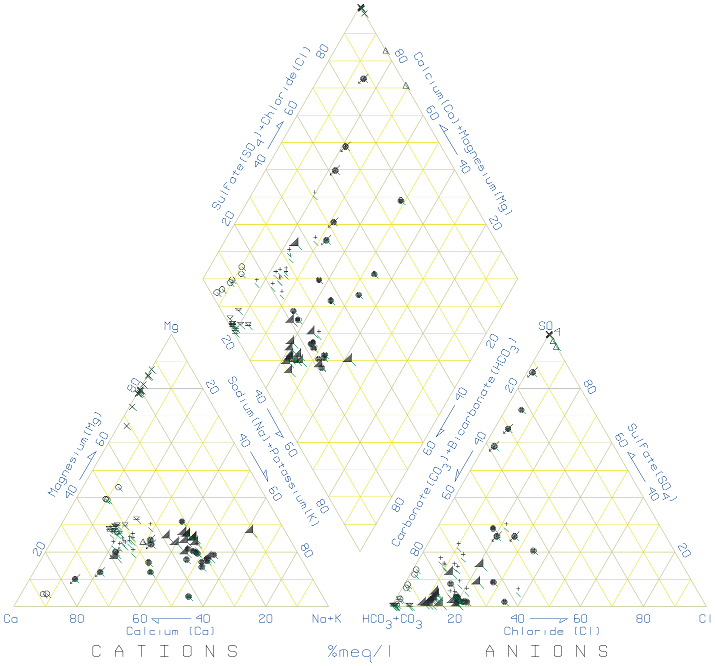
Geochemical baseline

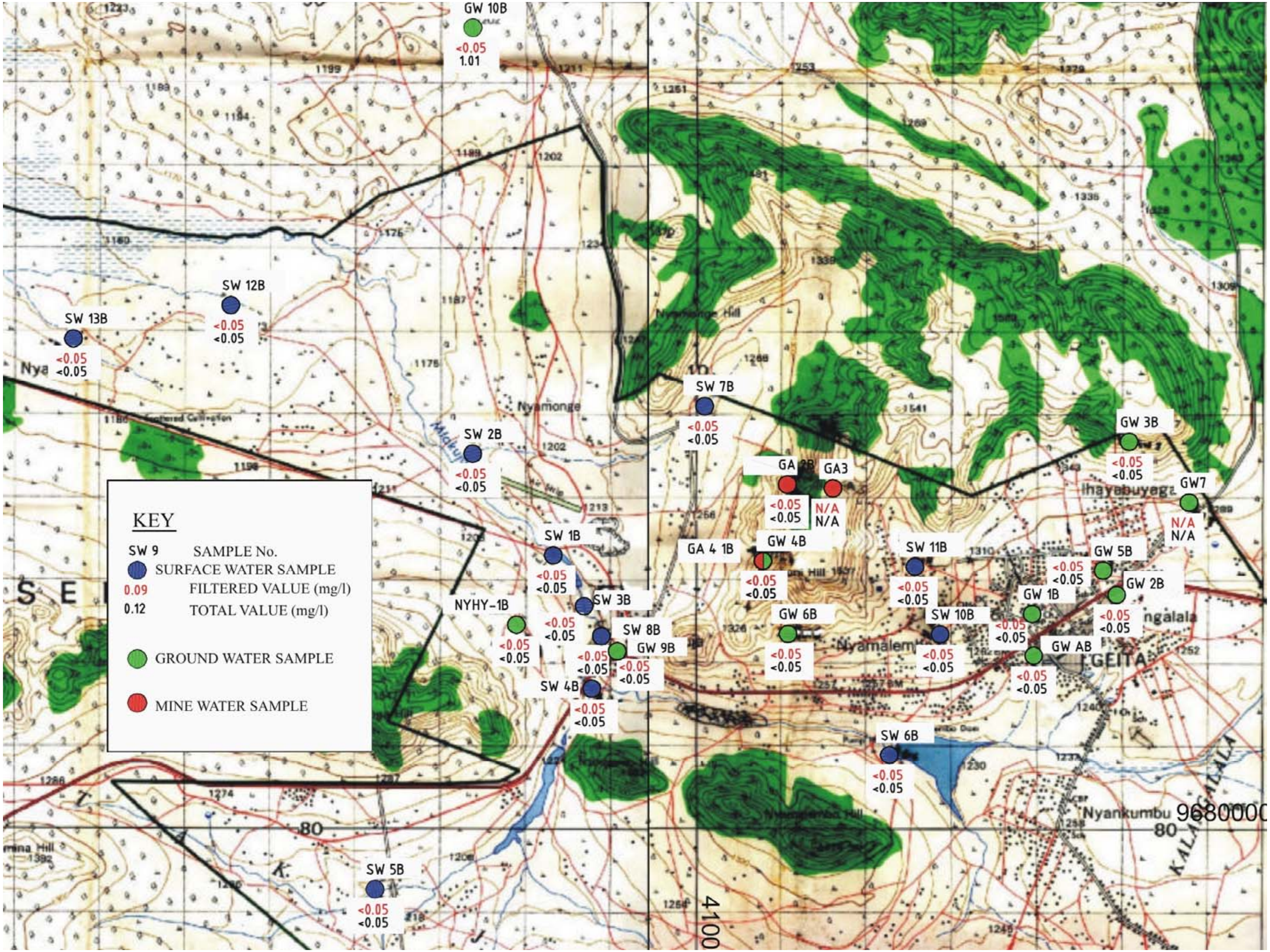
- Assessment of pre-mining conditions
- Establish realistic monitoring targets
- Establish closure goals on baseline values
- Sediment & water quality

Geita Project, Tanzania

- Surface water
  - Weathered zone leachate
  - Fertilizer contamination from farms
  - Artisan mining impacts (Hg)
  - Poor sanitation
  - Seasonal rain water

- Groundwater
  - *In-situ* sulfide mineralization (mine waters)
  - Bedrock hosting aquifers
  - Sanitation & water abstraction
  - Protolith vs regolith aquifers
  - Alkaline groundwater – can mobilize arsenic
  - Surface water low salt, low buffering (Na-Cl-HCO_3)



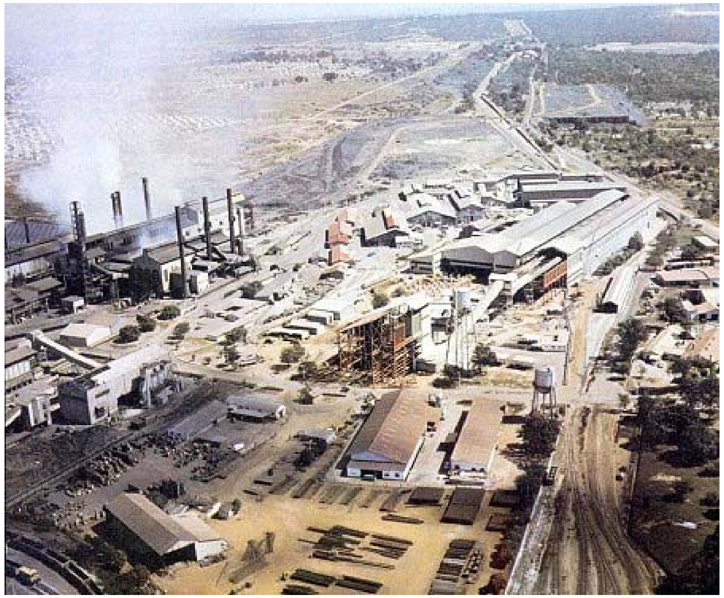

KEY
SW 9 SAMPLE No.
SURFACE WATER SAMPLE
0.09 FILTERED VALUE (mg/l)
0.12 TOTAL VALUE (mg/l)
GROUND WATER SAMPLE
MINE WATER SAMPLE
GW 10B <0.05 1.01
SW 12B <0.05 <0.05
SW 13B <0.05 <0.05
SW 7B <0.05 <0.05
SW 2B <0.05 <0.05
GA 2B <0.05 <0.05
GA3 N/A N/A
GW 3B <0.05 <0.05
GW7 N/A N/A
SW 1B <0.05 <0.05
GA 4 1B
GW 4B <0.05 <0.05
SW 11B <0.05 <0.05
GW 5B <0.05 <0.05
GW 2B <0.05 <0.05
GW 1B <0.05 <0.05
SW 3B <0.05 <0.05
NYHY-1B <0.05 <0.05
SW 8B <0.05 <0.05
GW 9B <0.05 <0.05
GW 6B <0.05 <0.05
SW 10B <0.05 <0.05
GW AB <0.05 <0.05
SW 4B <0.05 <0.05
SW 6B <0.05 <0.05
SW 5B <0.05 <0.05
Nyamonge
Nyamonge Hill
Ihayabuyaga
Nyamalembo
GEITA
Nyankumbu
9680000
80
4100

Summary of risk reactor pathways

Source	Pathway	Receptor
Acid generating minerals	Flushing of acid generating minerals during rainfall through vadose zone	Surface water Groundwater Sediments
	Transport of contaminants by groundwater flow	Domestic water supply wells Make-up water supply
Cyanide useage during mineral processing	Spill or release of cyanide and migration into vadose zone	Surface water Groundwater Aquatic species
	Contaminant transport in groundwater	Domestic water supply wells Make-up water supply
Mercury contamination from artisan mining	Spill or release and migration into vadose zone	Surface water Groundwater Aquatic specie
	Contaminant transport in groundwater	Domestic water supply wells Make-up water supply
	Sublimation of mercury during gold refining	Direct inhalation of fumes Dust deposition on flora

Environmental Geochemistry

- Pre-mining assessment
- Impacts to air – smelter emissions, spray from heap, dust, mineral particles e.g. quartz, asbestos
- Impacts to water – acid/alkaline, metals, metalloids, salts
- Impacts to soil – metals/metalloids/oil
- Social and political – product of above, generates poor perception “bad neighbour principle”



Air Quality

- Smelter emissions
- Sulfur output high
  - Bor~1200 tons SO_2 pa
- Loss of volatiles
  - Bor ~250 tons As pa
  - Bor ~120 tons Hg pa
- More historical than contemporary as an issue
- Create wide dispersion and semi-regional impact
- Dust dispersion of fine solids from impoundments, waste dumps etc

Impacts to Water

- Elevated metals, metalloids & sulfur
- Acid Generation
- Impacts to groundwater
- Impacts to surface water

Processes active in weathering

DISPERSION

- Mineral weathering
  - Sulfide oxidation
  - Salt dissolution
  - Mineral buffering
- Desorption
- Cation Exchange

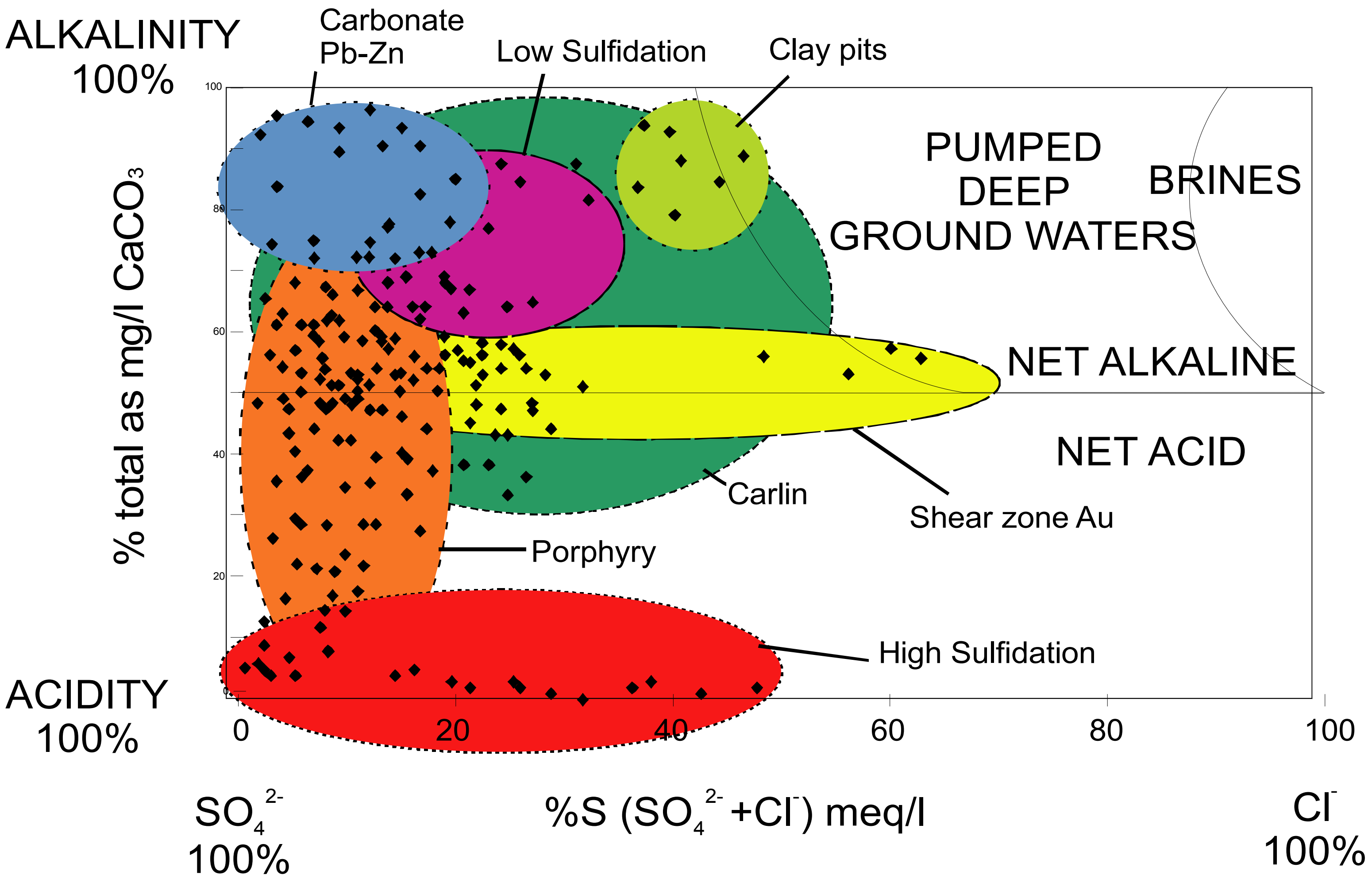
ATTENUATION

- Mineral precipitation
  - Solubility control
  - Trace element incorporation
- Adsorption
  - Surface effects
- Absorption
  - Cation Exchange
  - Metal Scavenging

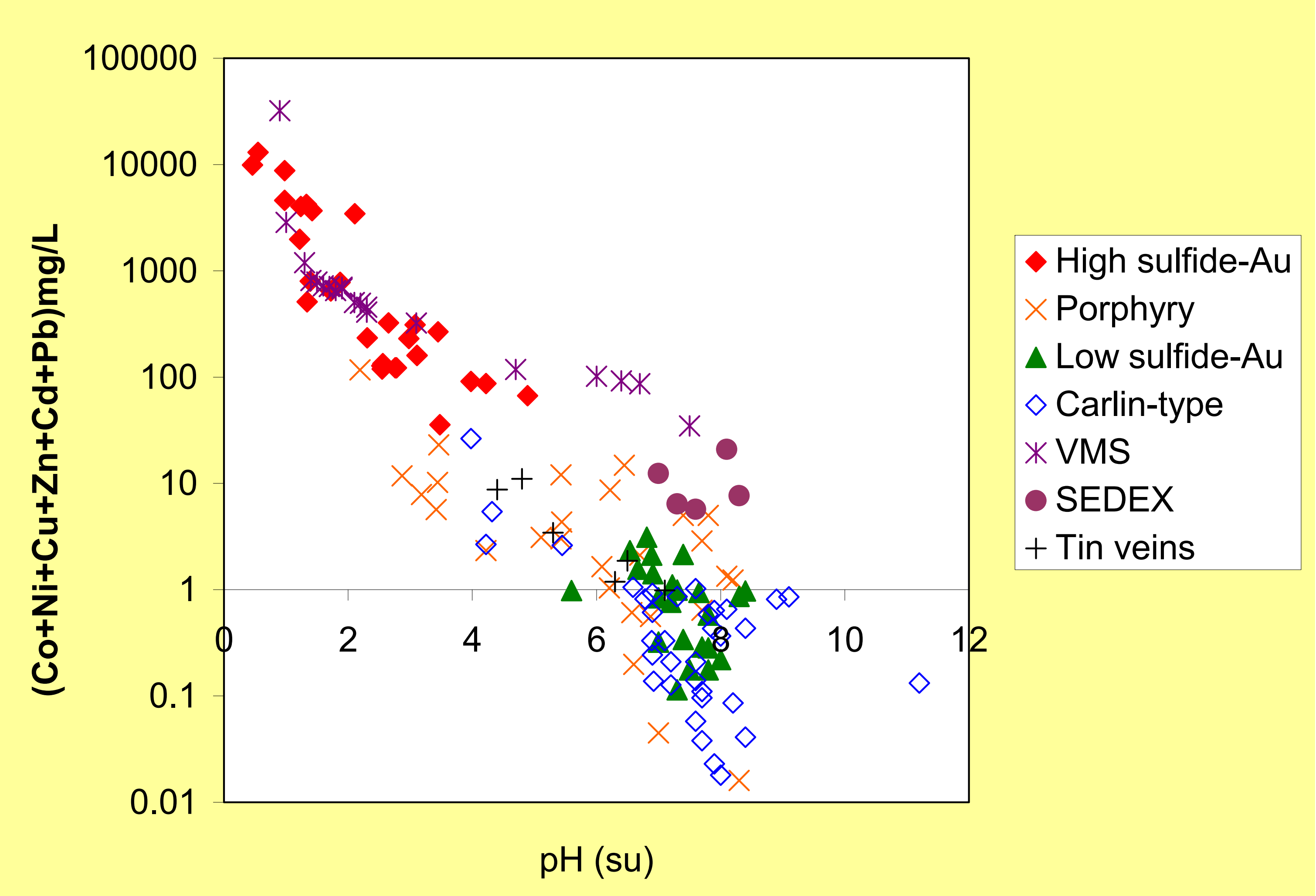
Generation of Acid Rock Drainage

- Driven by mineral stability or instability
- Sulfide or acid sulfate source
- Limitation on carbonate buffering

Implications for Hydrogeochemistry, Younger plot



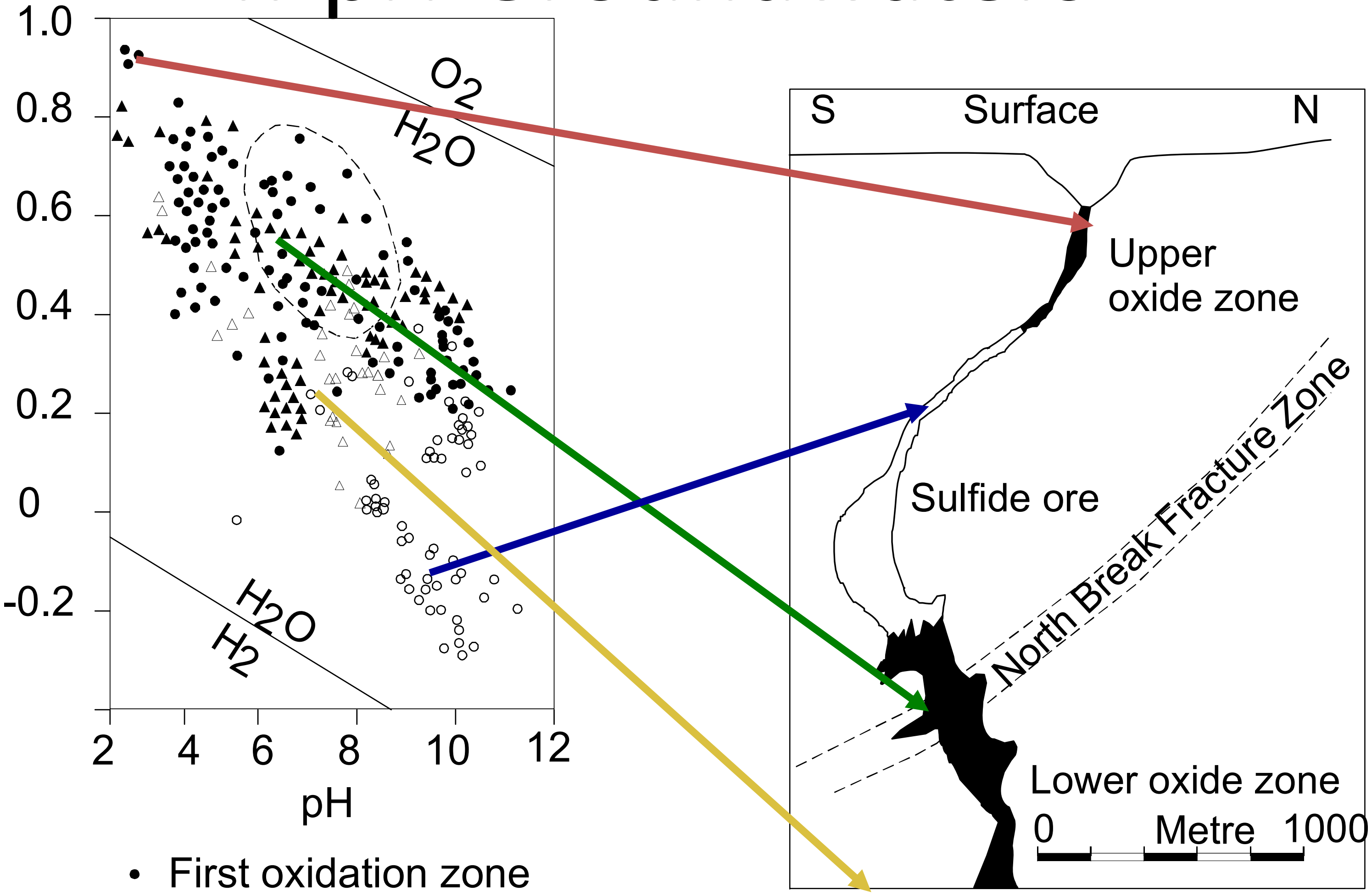
Metal chemistry in drainage, Ficklin plot



Case study: Tsumeb, Namibia

- Polymetallic pipe-like deposit
- Precambrian age dolomite host
- Pan African mineralization
- 1908-1993 operation
  - 5Mt Cu, 9.5 Mt Pb
  - Zn, Ag, Au, Cd, Ge, As, Sn, W, V, Mo, Co, Hg, Ga, In, Sb

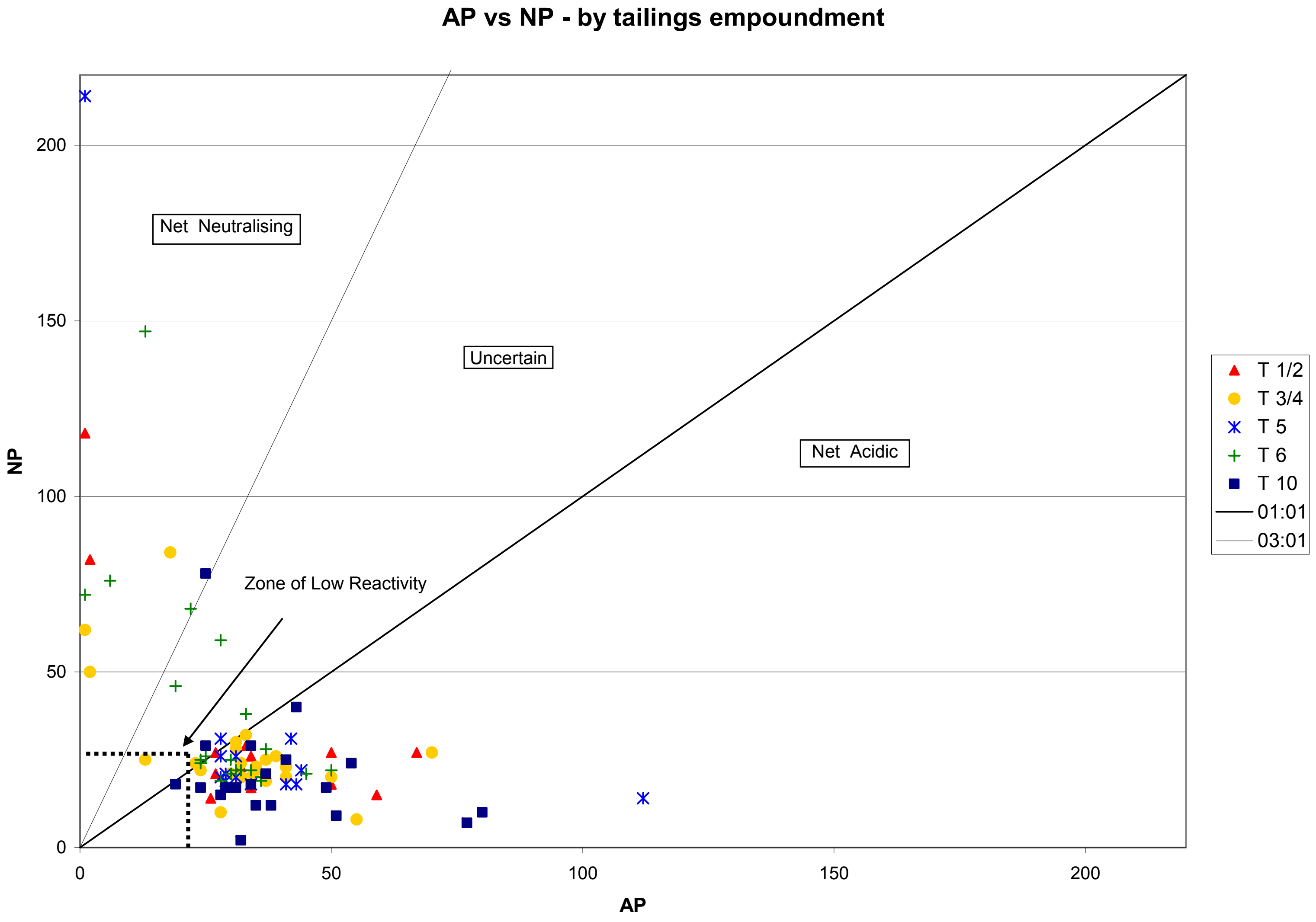
Eh-pH Groundwaters



- ● First oxidation zone
- ▲ Second oxidation zone

- ○ First sulfide zone
- △ Second sulfide zone

Acid Base Accounting



Humidity Cell Testing (HCT)

- ASTM D 5744 - compare to other datasets directly
- 40 week program (equivalent to 10,000 yrs of meteoric water infiltration contact)
- Weathering rates – accelerated
- Minimal sulfide oxidation often until week 40+

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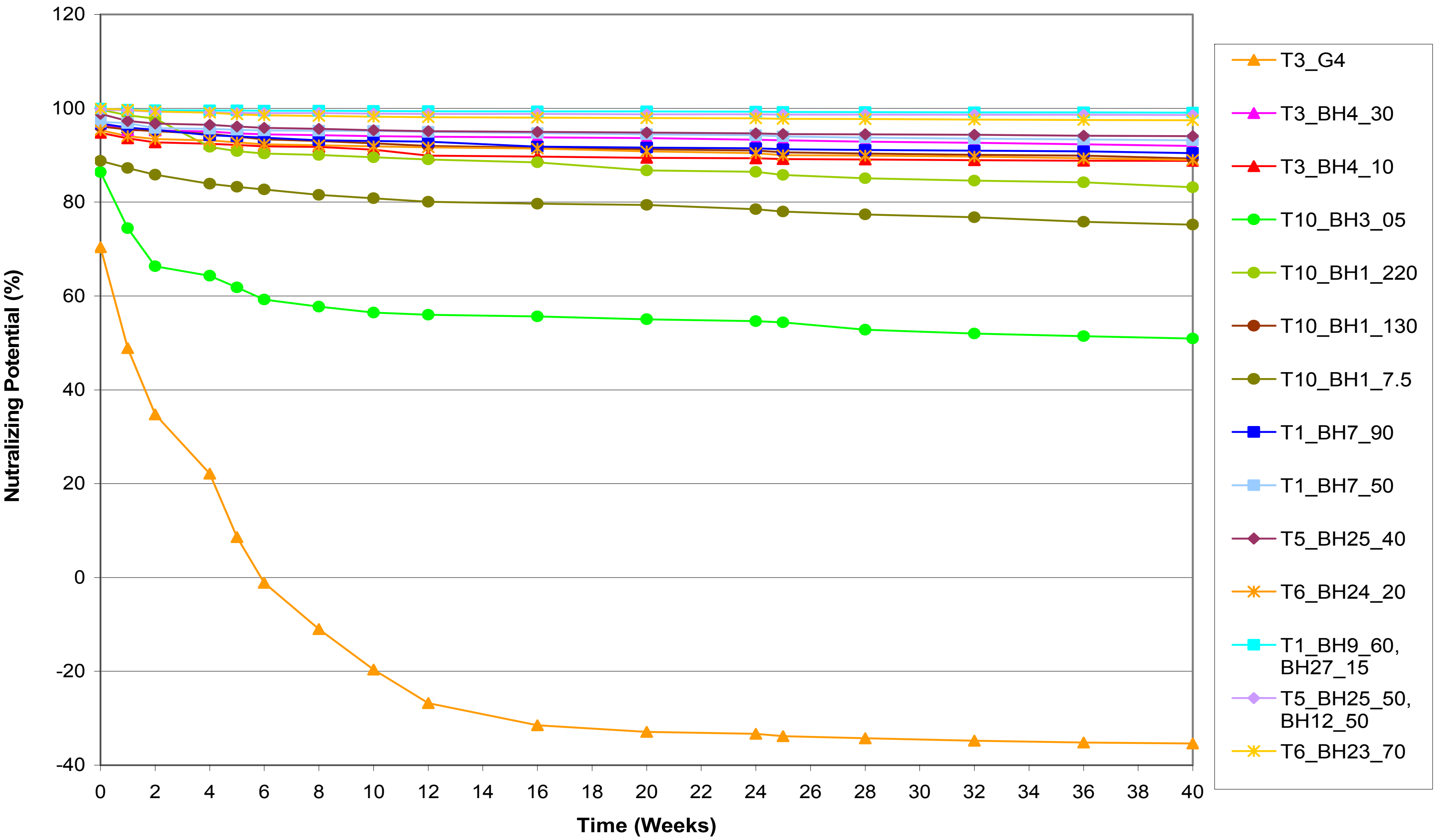
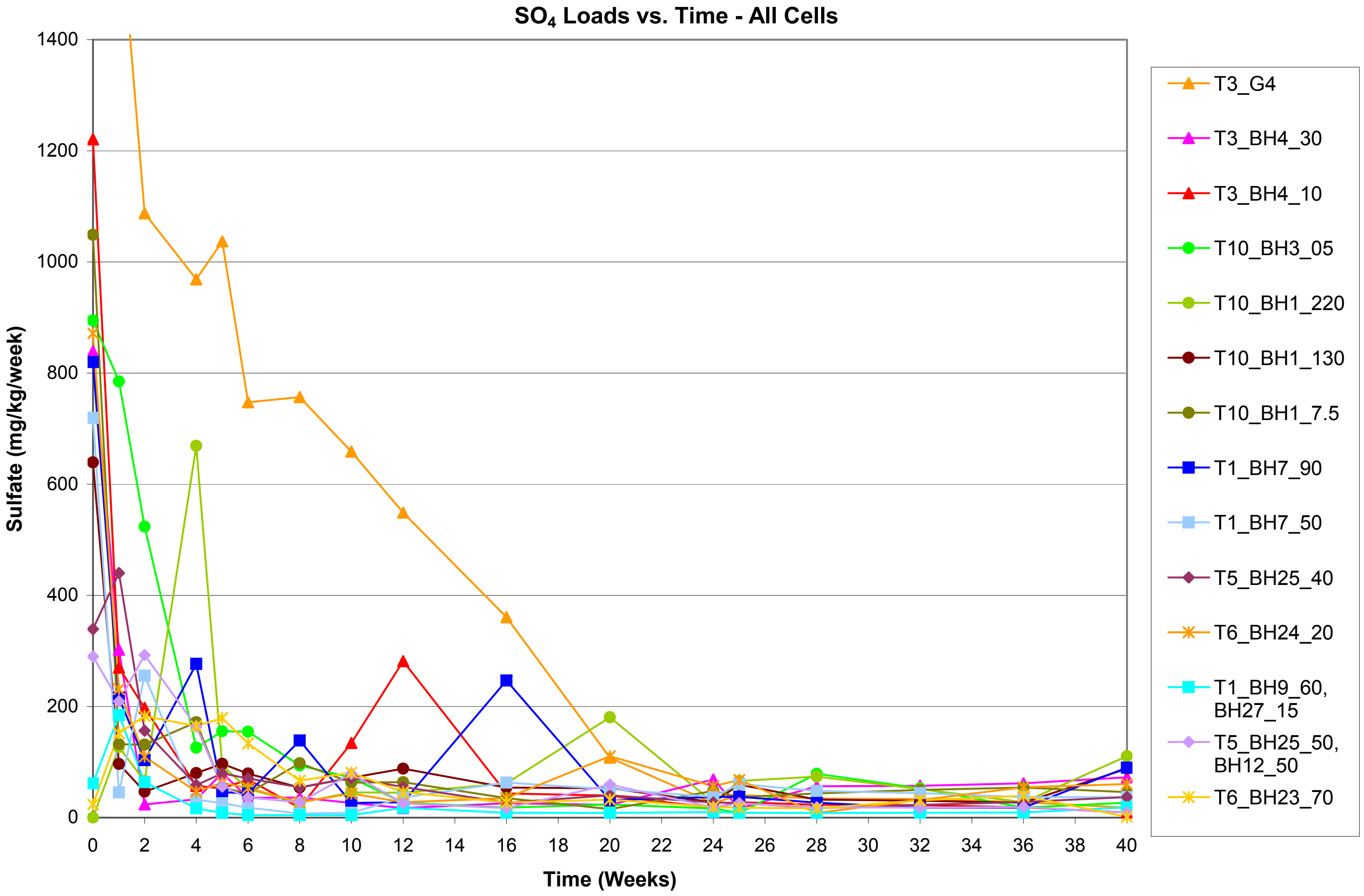
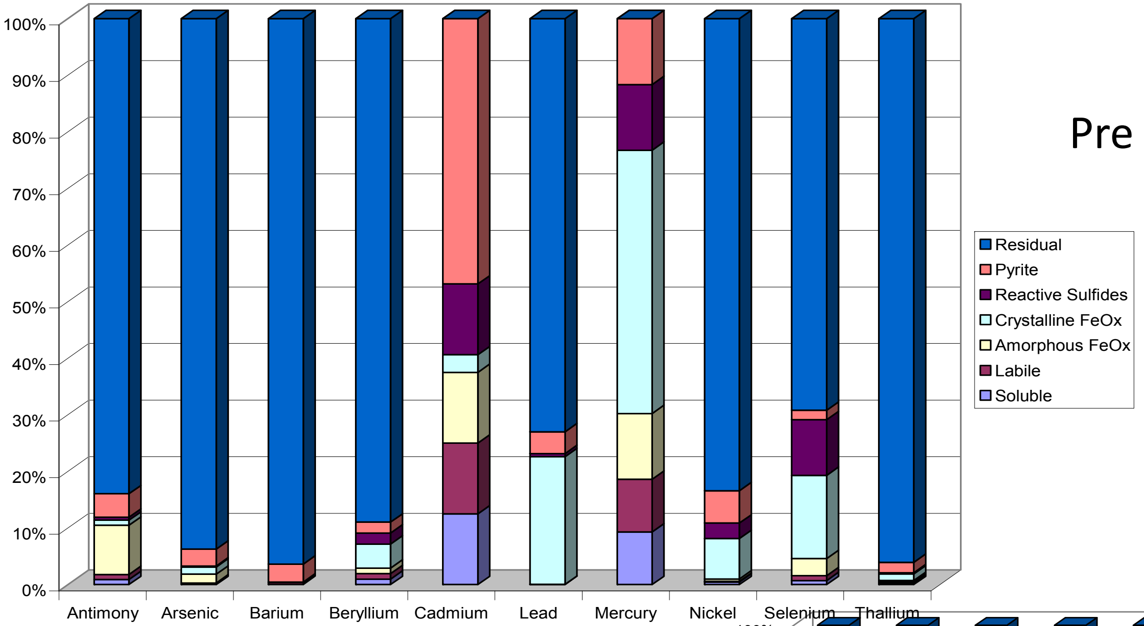
Consumption of Neutralization Potential



HCT Load Release: Sulfate

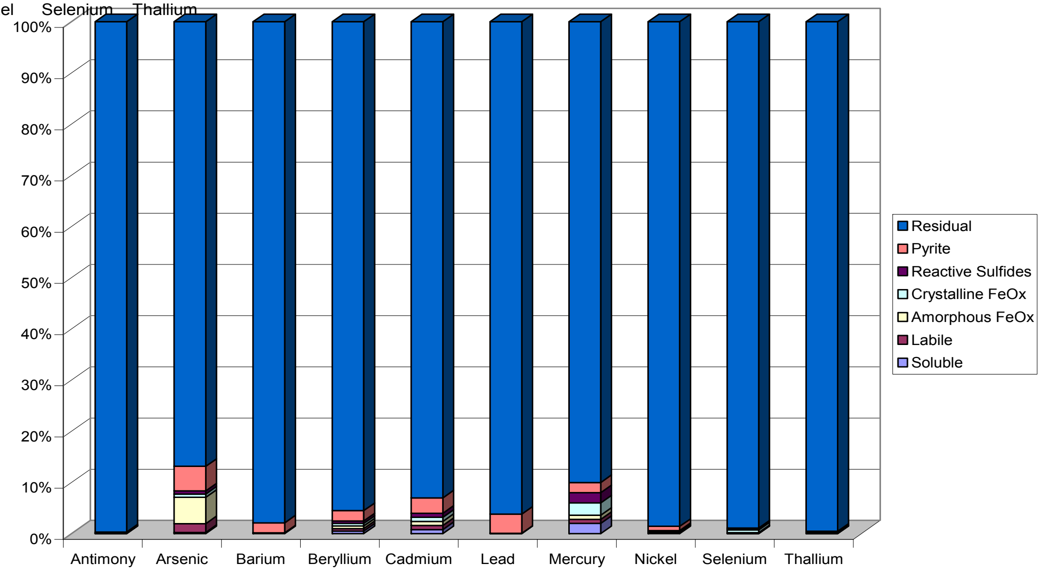


Metals Speciation in Minerals

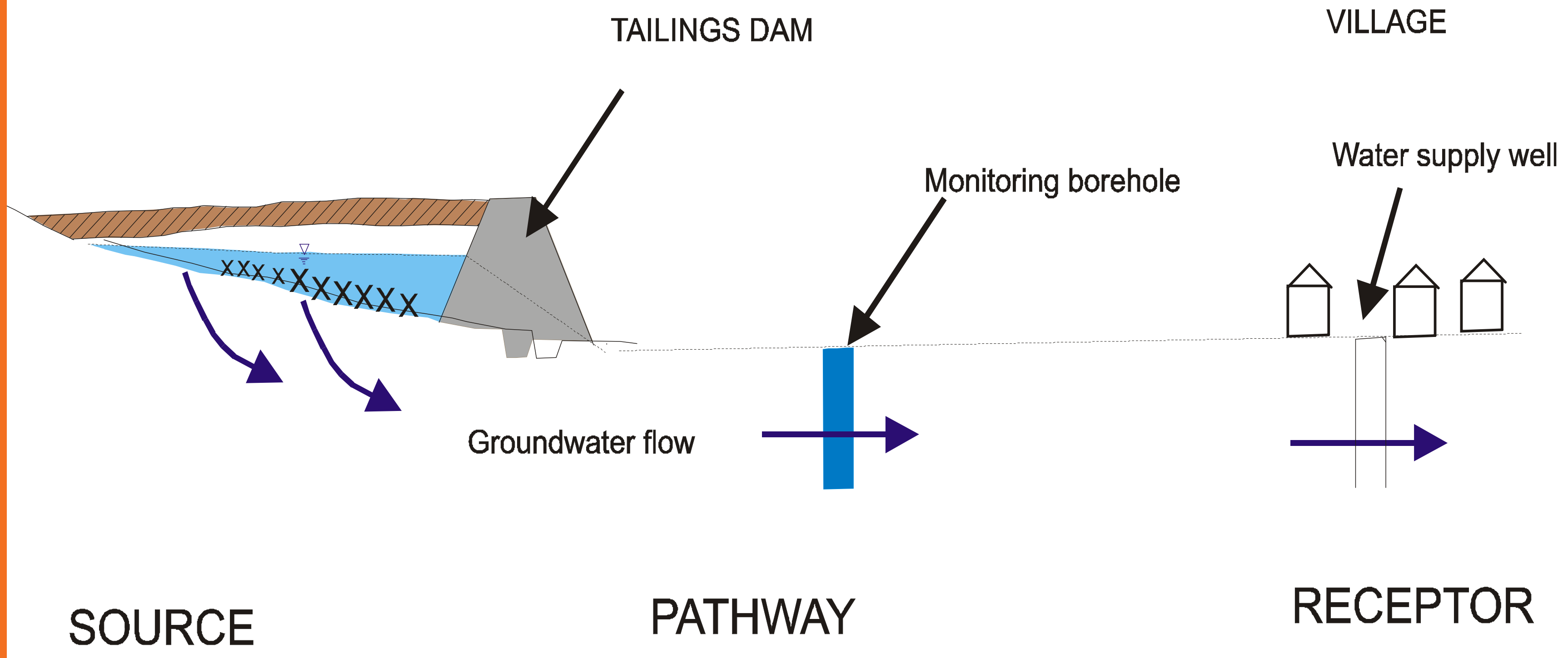


Pre HCT

Post HCT



Prediction of Future Geochemistry



TAILINGS DAM

VILLAGE

Water supply well

Monitoring borehole

Groundwater flow

SOURCE

PATHWAY

RECEPTOR

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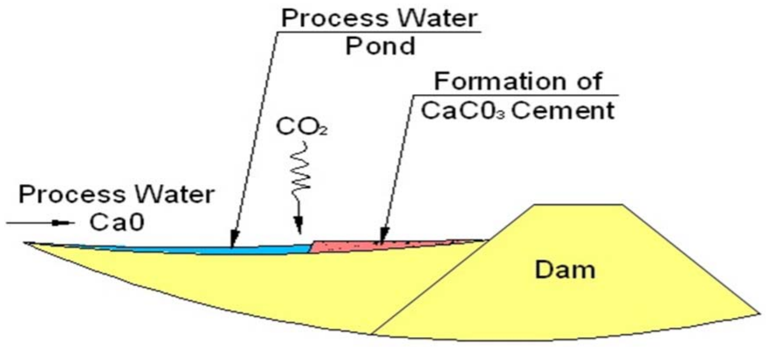
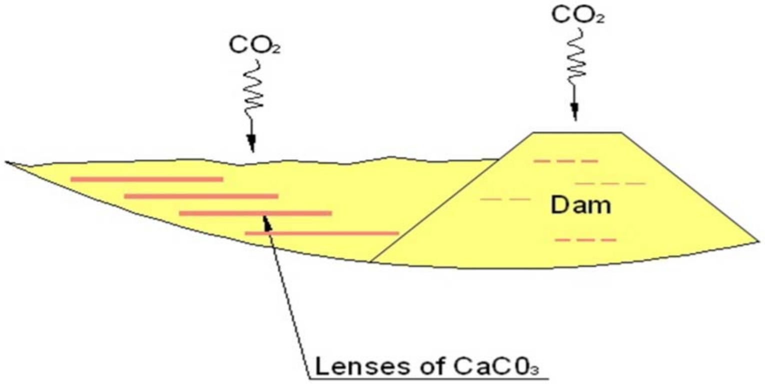
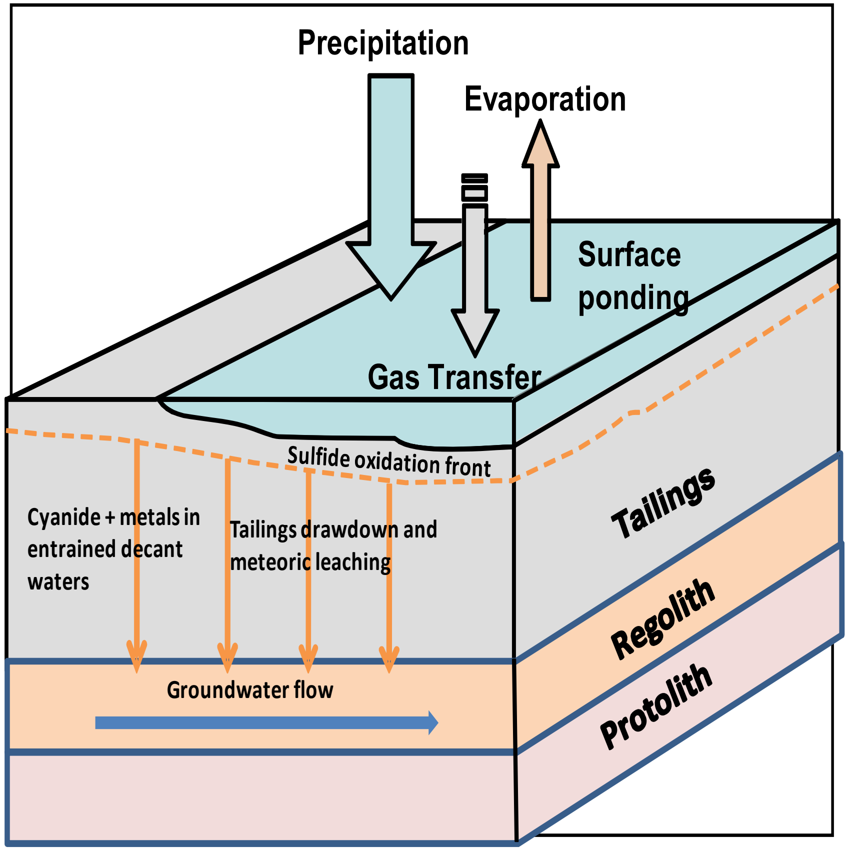
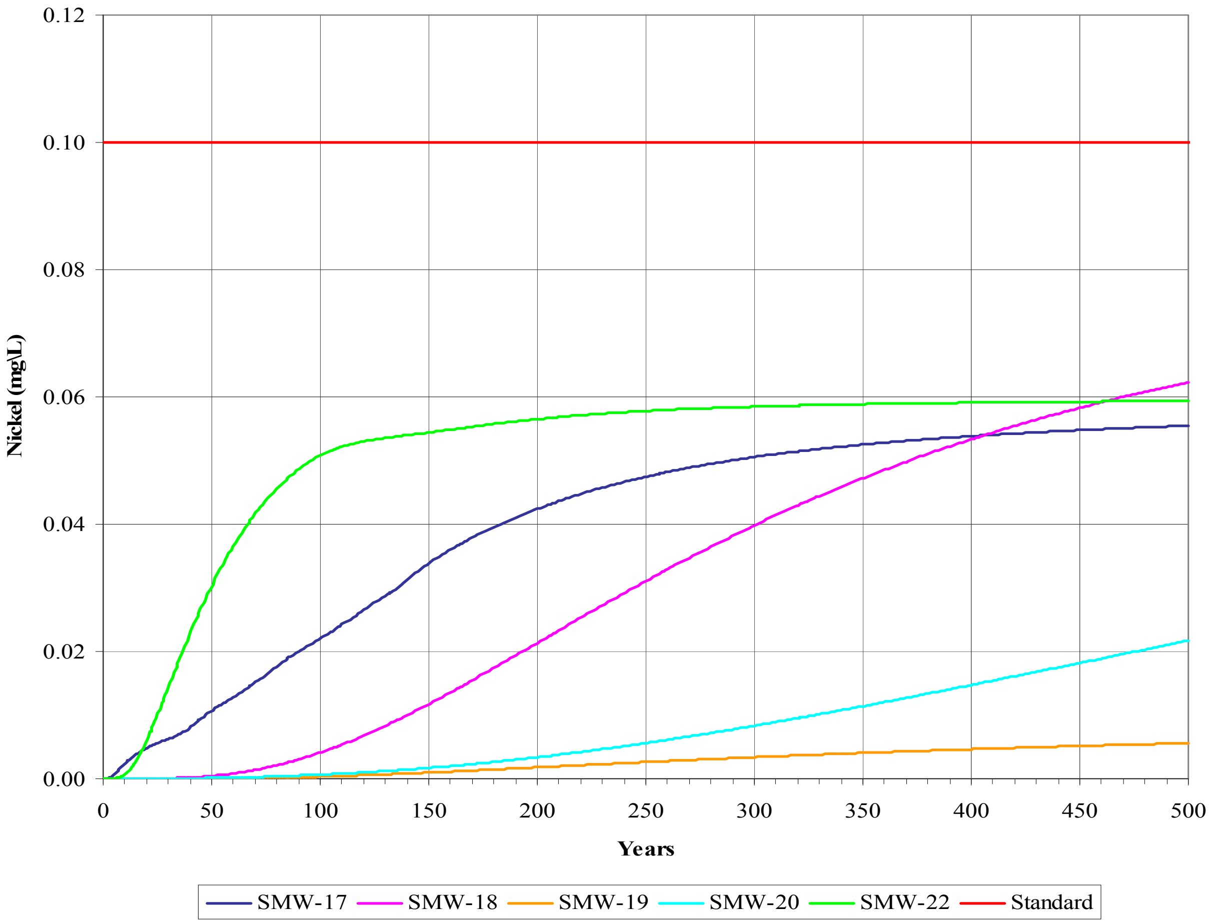
Conceptual Evaluation of Tailings Geochemistry





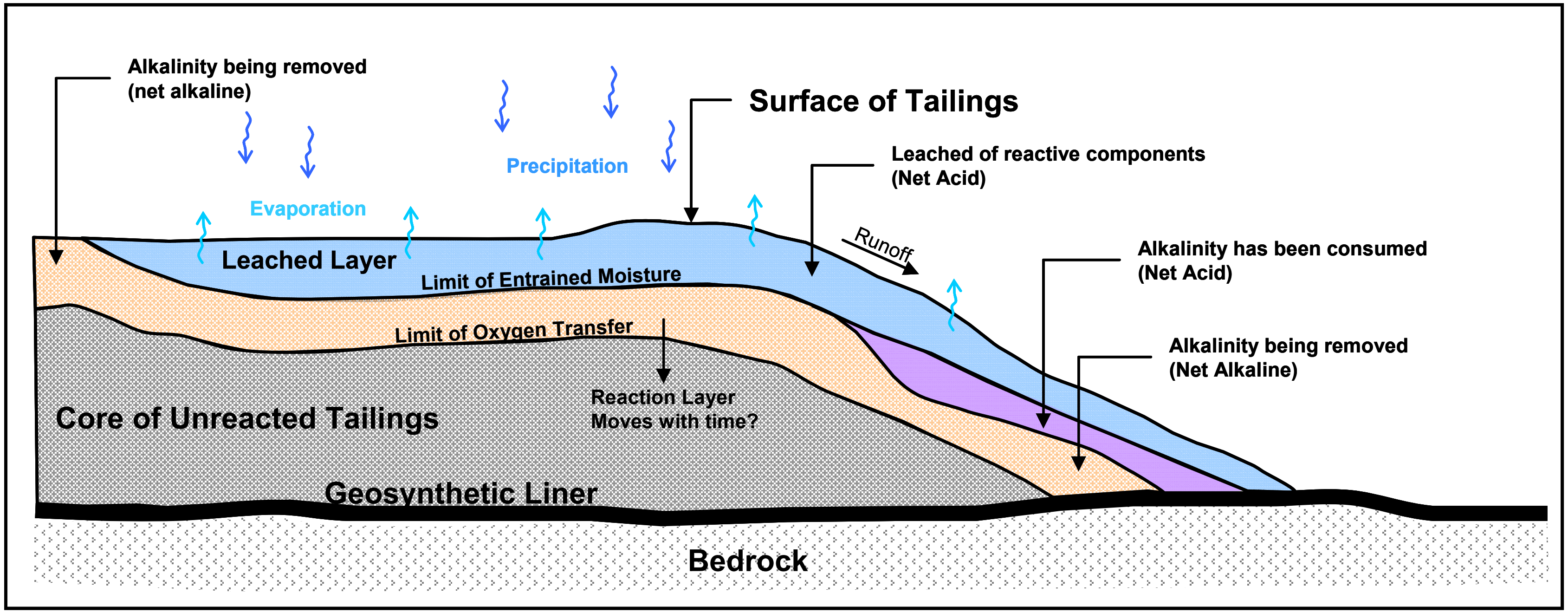


Groundwater Model Predictions



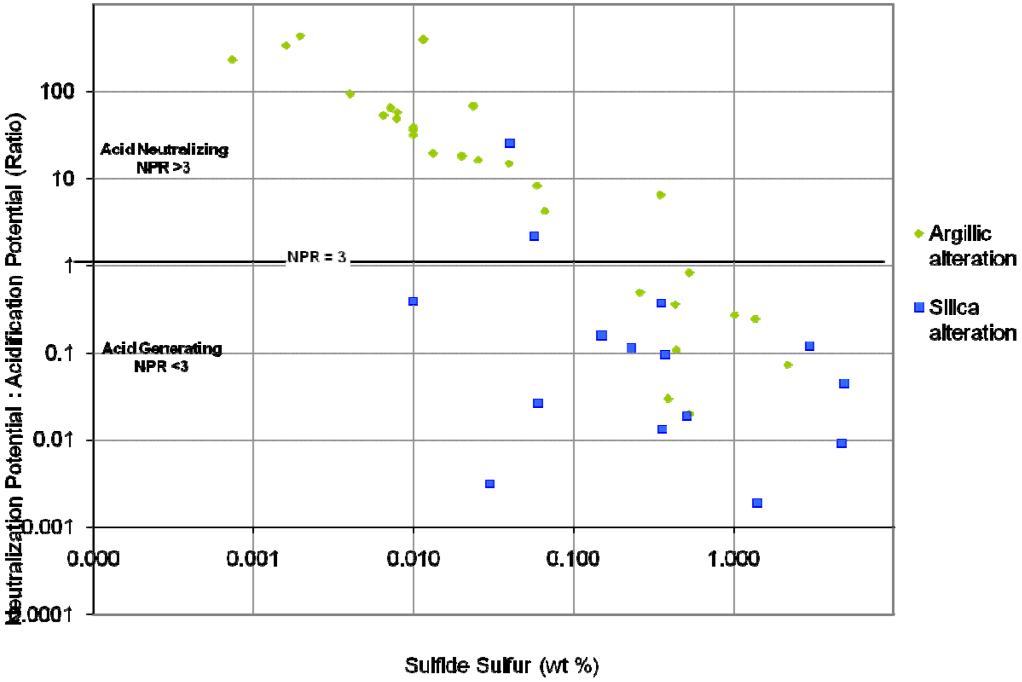
Parameter	AWQS (mg/L)	Maximum (mg/ L)
Antimony	0.006	0.0016
Beryllium	0.004	0.00060
Cadmium	0.005	0.0016
Nickel	0.1	0.051
Selenium	0.05	0.0046
Thallium	0.002	0.00013

Interpretation of TMF Geochemistry



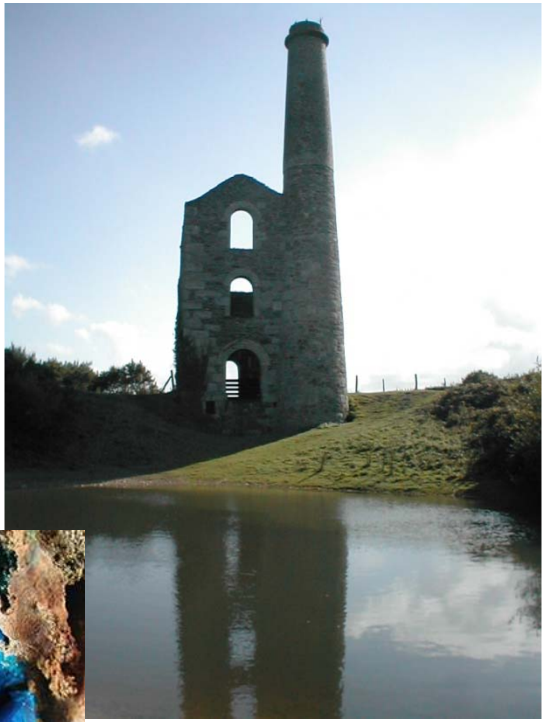
Historic Waste Rock Management

- Mixed waste rock
- Impacts to off site water resources
- Physical stability
- Chemical stability
- Economic issue



Geochemistry of Toxicity?

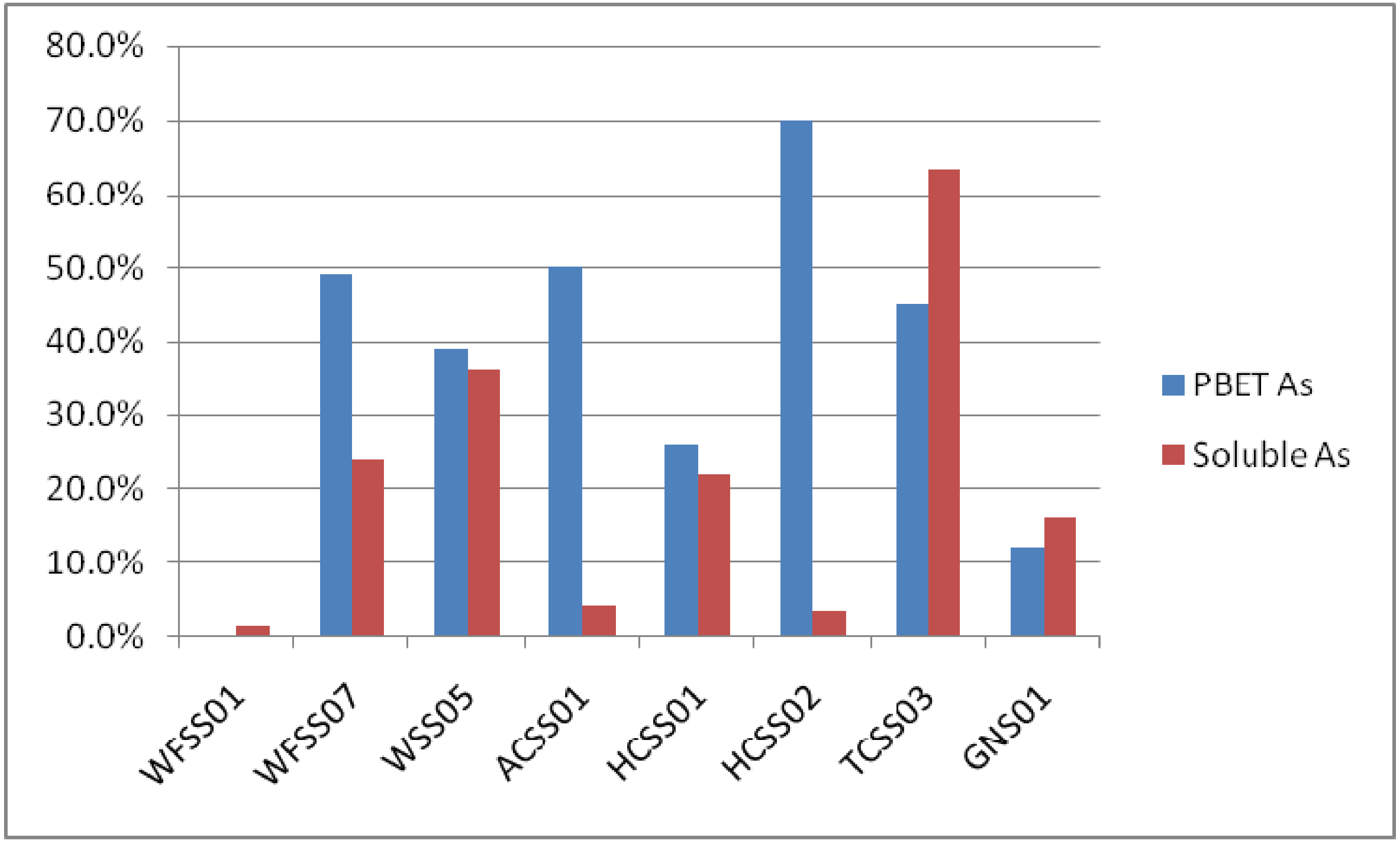
- Former area of Sn-Cu-As mining
- Relicts of past mines and process sites from 1300's to early 1900's
- UNESCO world heritage site
- Tourism, Cultural & Reclamation value
- Risk of Arsenic toxicity



Arsenic toxicity test

- PBET test
- Simulate gastrotestinal consumption
- Several sequential extractions at 37°C
- Bioavailability risk assessment

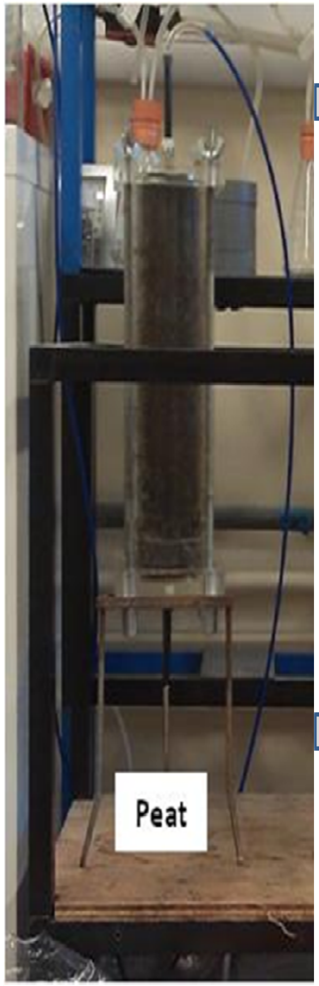
Correlation with Mineral Phases

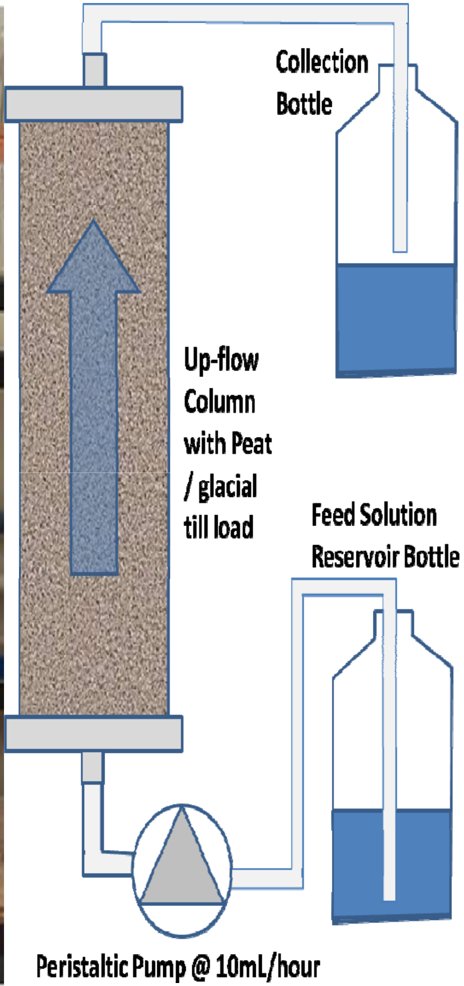


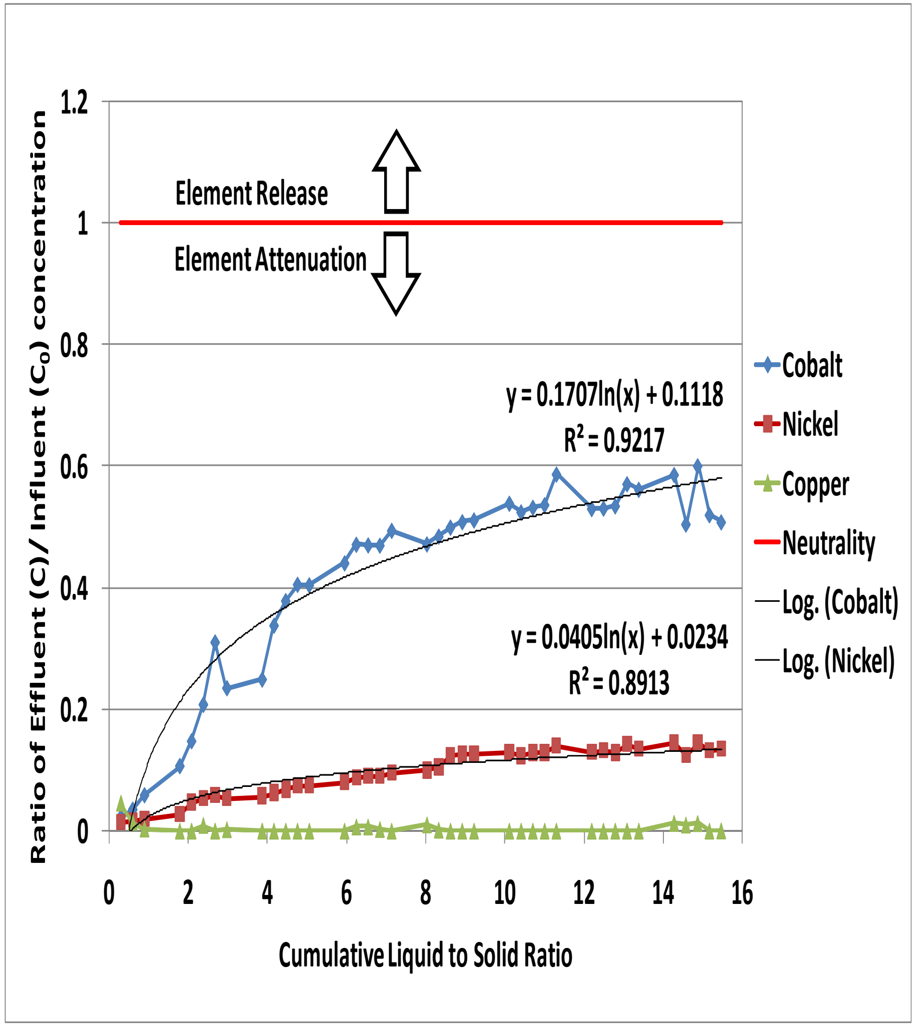
Assessment of Water Clean-up

- Determine geochemical characteristics of water
- Determine health risk
- Utilize geochemical modelling to predict long term trends
- Define chemical reactions required to meet Water Quality/Health Requirments

Passive Attenuation





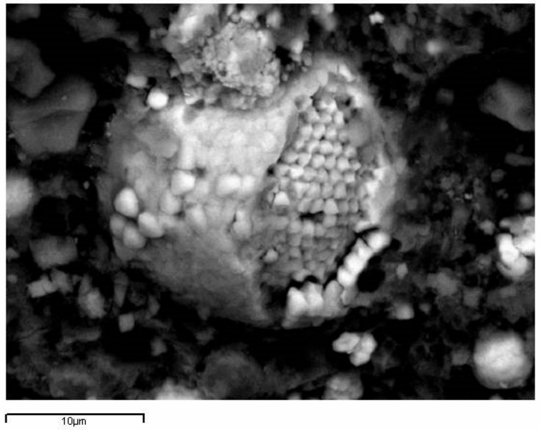


Mining geochemistry issues

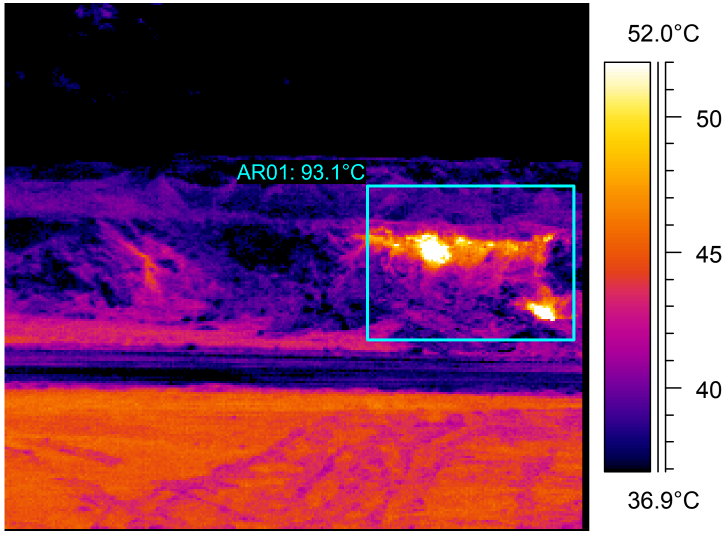
- Material strength- presence of clays, reactive minerals
- Pyrite oxidation- fires in shale/coal
- Ore dilution
  - Lower grade
  - Presence of smelter penalty elements
- Water management
  - Especially with ISR
- Environmental limitations
- Objectives
  - Improve efficiency of mining & processing
  - potential water quality issues
  - sensitivities in prediction
  - sensitivity in the receiving environment
  - potential mitigation measures

Cerrejon coal, Colombia

- Pyrite oxidation in interburden
- Highly pyritic zones in both burning & non-burning areas
- Loss of 70k+ tonnes of coal pa
- Pyrite oxidation in inter-burden
- Fine grained, porous pyrite
- Rapid kinetics- oxidation
- Exothermic reaction
- Impact on water quality- sulfate, metals
- Not acceptable but;
  - Can it be solved?
  - Can it be predicted?



Thermograph- identify hot spots



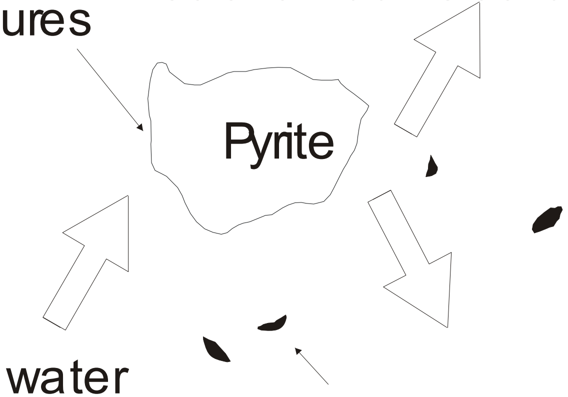
Base **3**. Thermograph

ambient temp. 29^{o}C

Relative Humidity 60%

Explanation

- Identify source components
- Identify susceptible seams and interburden
- Alter mining schedule
    - –Reduce exposure time
    - –Reduce oxidation
    - –Preserve coal
- Net benefit- environmental & economic



Oxygen diffuses along fractures

Heat from oxidation reaction burns carbon

Pyrite

Fluid flow- water

Carbon in shale

Antamina, Peru

- Open Pit
  - Copper, zinc skarn deposit
  - 500 x 10^6 t ore
  - 1.3 x 10^9 t waste rock
  - 22 yr mine life @70,000 tpd
- Products
  - Copper Concentrate
  - Zinc Concentrate
  - Molybdenum Concentrate

Peaks Waste Rock Program

- Constraints
  - Geochemical
    - Must not leach metals or acidity (react with concrete)
  - Physical
    - Rock strength and particle size for construction
  - Appearance
- Background
  - Peak rock primarily hornfels, marble and limestone
  - NP >400 kg $CaCO_3$/t
  - However, occasional samples to 4%S, 2.4% Zn

Waste Rock Characterization

- Visual classification is confirmed
- Visual approach is conservative
- Timely geochemistry analyses may modify
  - "Reactive" A
    - skarn, green hornfels, & intrusive with sulfide,
    - >700 ppm Zn, > 2% sulfide
  - "Slightly reactive" B
    - mixture of A & C, analyses might show more C
  - "Non-reactive" C
    - <200 ppm Zn, <2% sulfide
    - Tr-2% Py & Po, minor iron oxide staining

Operational Implementation

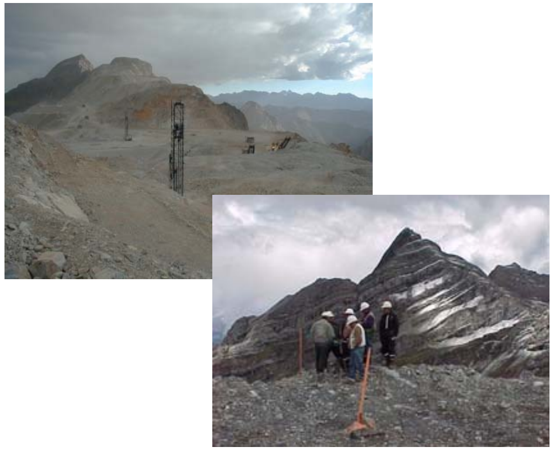
- Geology
  - Mapping blastholes, benches, highwalls, dig faces
  - Shift by shift communication with operations and engineering
- Planning (for mining rock classes A B C)
  - Daily ABC bench maps
  - Compiled geology, geochemistry, ABA data (Gemcom plots)
  - Month's end "next bench" predictive map
- Reconciliation
  - Tracking maps & dispatch system

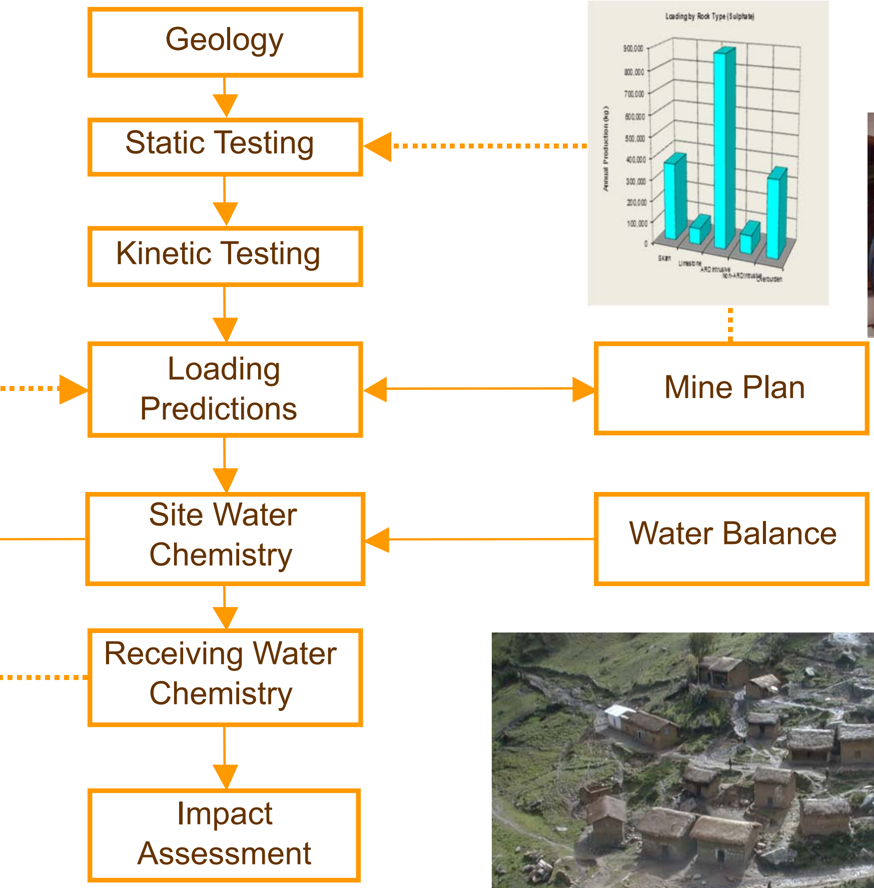
Peak Rock Handling

Peak Rock Handling

- A: Reactive
  - Drainage management planned – East Dump
- B: Slightly reactive/needs testing
  - Drainage can be controlled – roads, foundations in tailings basin
- C: Non-reactive
  - Tailings dam construction

Waste Management





Geology

Static Testing

Kinetic Testing

Loading Predictions

Mine Plan

Mine Rock Management

Site Water Chemistry

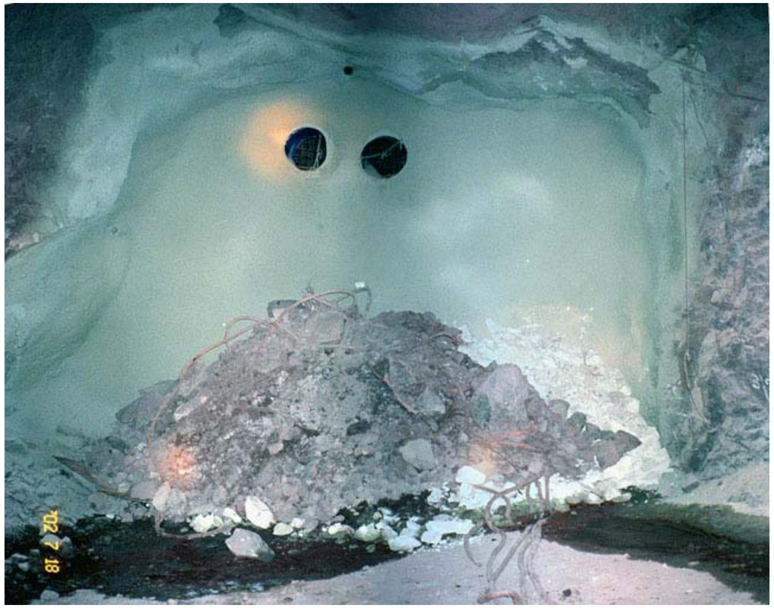
Water Balance

Receiving Water Chemistry

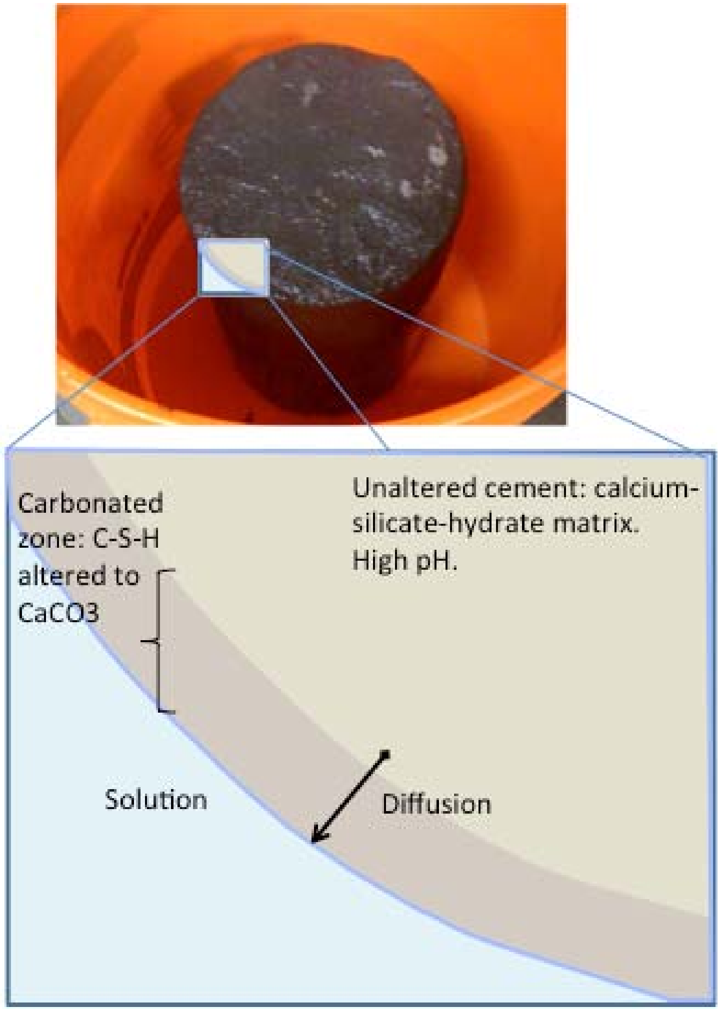
Impact Assessment

Case Study: Paste backfill

- Underground mine fill
- High acid generation potential
- Highly reactive rocks
- Corrosive to conventional cement
- Rapid mix-key (less time for oxygen/water reaction)
- Develop understanding of geochemical stability in order to determine physical stability
- Develop site specific assessment protocols



Geochemical assessment, CPT

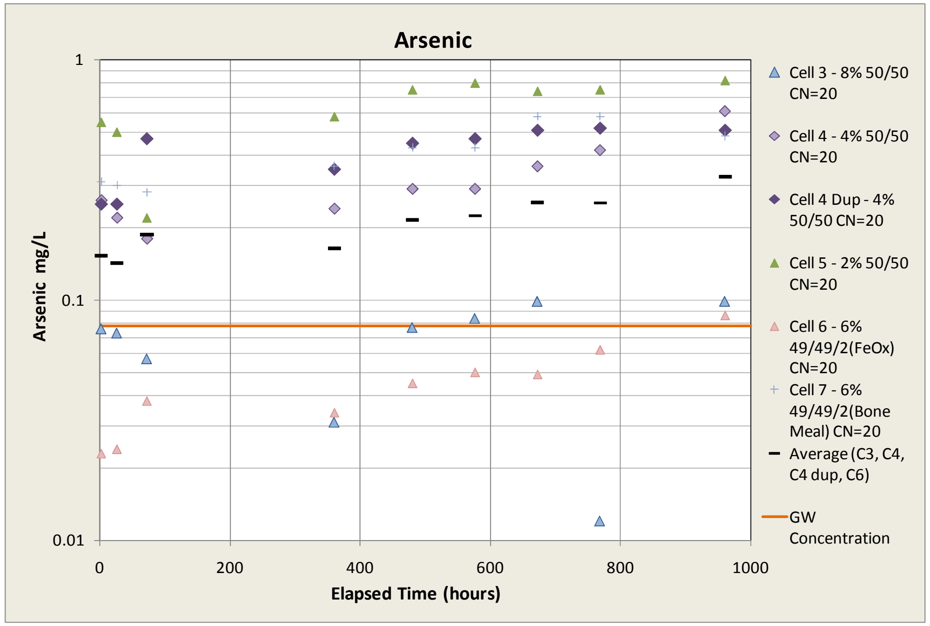


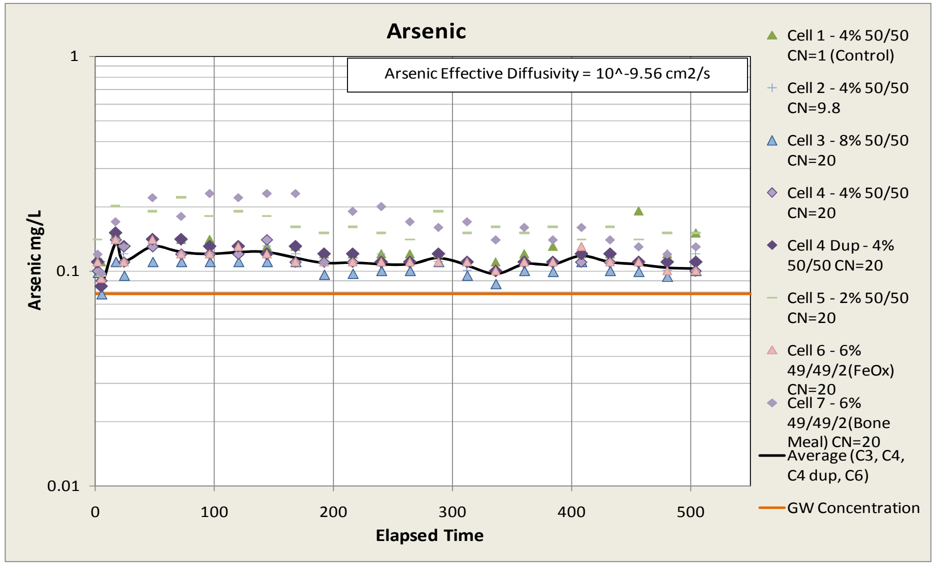
Carbonated zone: C-S-H altered to CaCO3

Unaltered cement: calcium-silicate-hydrate matrix. High pH.

Solution

Diffusion

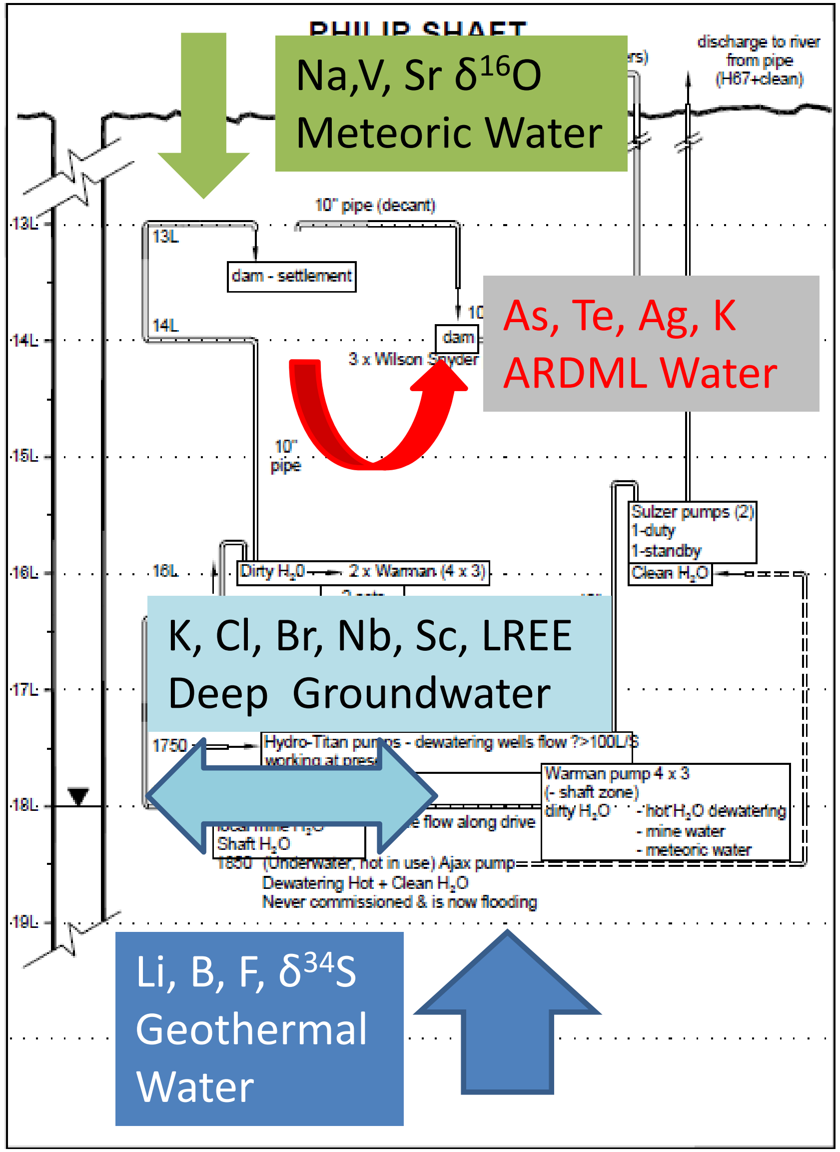




Emperor mine, Fiji

- Caldera associated epithermal Au-Ag-Te & porphyry Cu mineralization
- Pumping of groundwater as part of dewatering scheme
- Hot, saline groundwater (>70°C; 1600 mg/L)
- High SO_4 & F
- Trace elements also present in water

Geochemical tracers in Water Management



Na,V, Sr $\delta^{16}O$
Meteoric Water

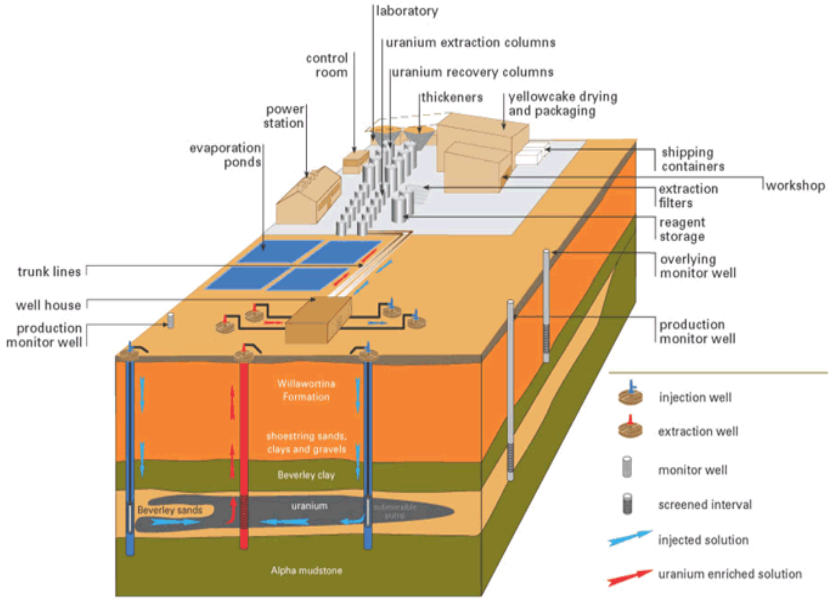
As, Te, Ag, K
ARDML Water

K, Cl, Br, Nb, Sc, LREE
Deep Groundwater

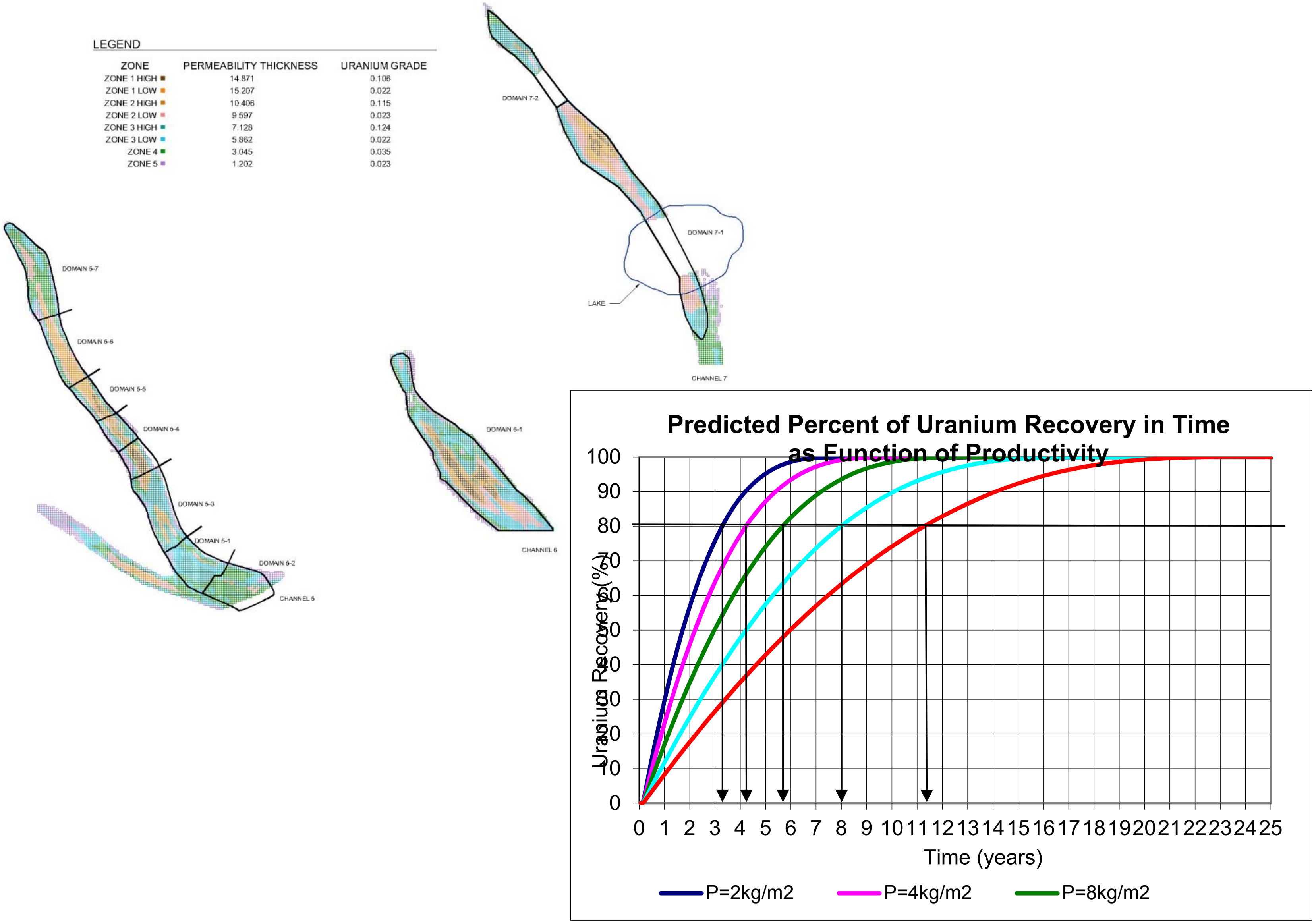
Li, B, F, $\delta^{34}S$
Geothermal
Water

In Situ Recovery: Geochemical Mining

- In-Situ Leaching of commodity
- Pump loaded groundwater to recovery plant
- Potash, Salt, Uranium & Copper
- Possibly Gold? Possibly Nickel?
- No physical disturbance
- Focused in ore bearing zone



Geochemical Resource Evaluation

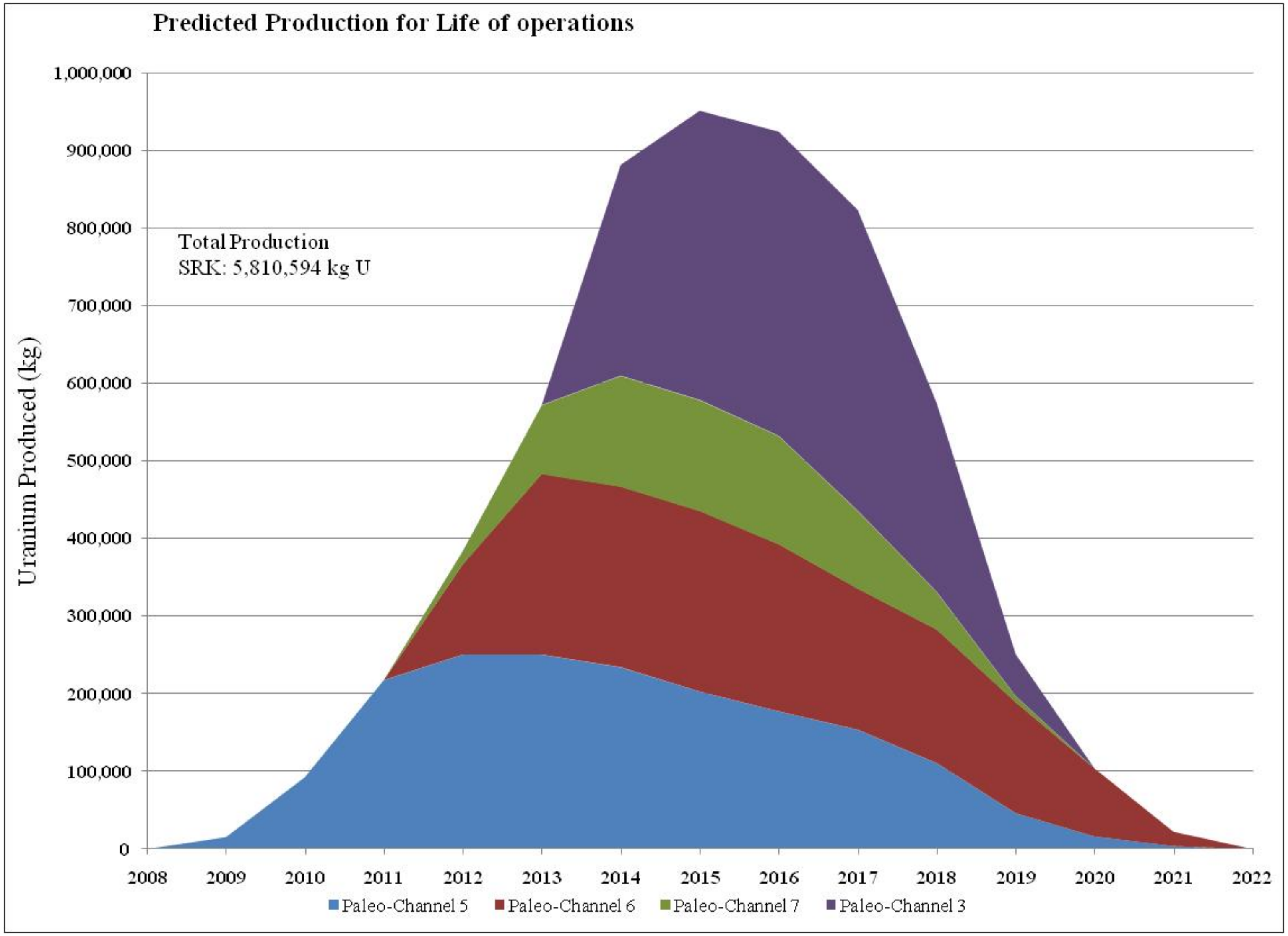


LEGEND

ZONE	PERMEABILITY THICKNESS	URANIUM GRADE
ZONE 1 HIGH ■	14.871	0.106
ZONE 1 LOW ■	15.207	0.022
ZONE 2 HIGH ■	10.406	0.115
ZONE 2 LOW ■	9.597	0.023
ZONE 3 HIGH ■	7.128	0.124
ZONE 3 LOW ■	5.862	0.022
ZONE 4 ■	3.045	0.035
ZONE 5 ■	1.202	0.023

Predicted Percent of Uranium Recovery in Time as Function of Productivity

Geochemical Predictions

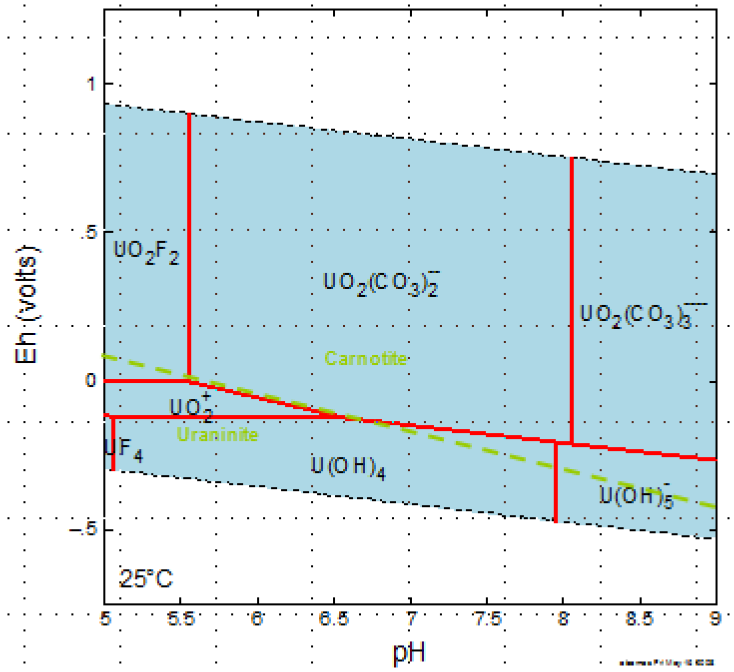


Mineral Processing: Transition

- Historic
  - Ore close to surface
  - Oxide zone
  - High grade
  - Easy to process
- Currently
  - Deeper ore
  - Chemically complex ores
  - Variable grade
  - Refractory

Geochemistry matters-uranium

- Uranium has two oxidation states, IV and VI
- Hexavalent is the most oxidized and soluble form, as UO_2^{2+}
- In Uranium minerals, uranium present in crystal lattice – most commonly as U IV – requires oxidizing agent to release



Good copper, Bad copper

Gold-Copper deposits are common;

Good Copper

- Chalcopyrite/Bornite; not soluble in cyanide, easily concentrated by floatation

Bad Copper

- Azurite, malachite, covellite; soluble in cyanide
- Enargite; high As

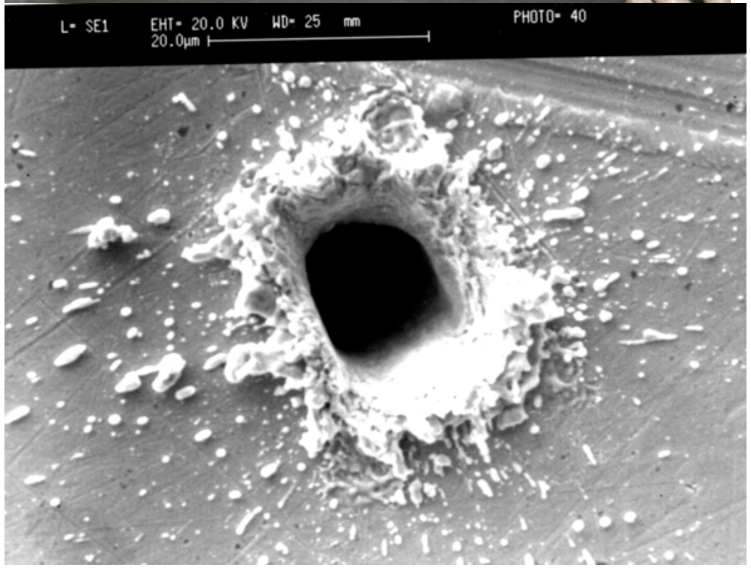
Assay for CN soluble Cu

Gold's unwanted relatives

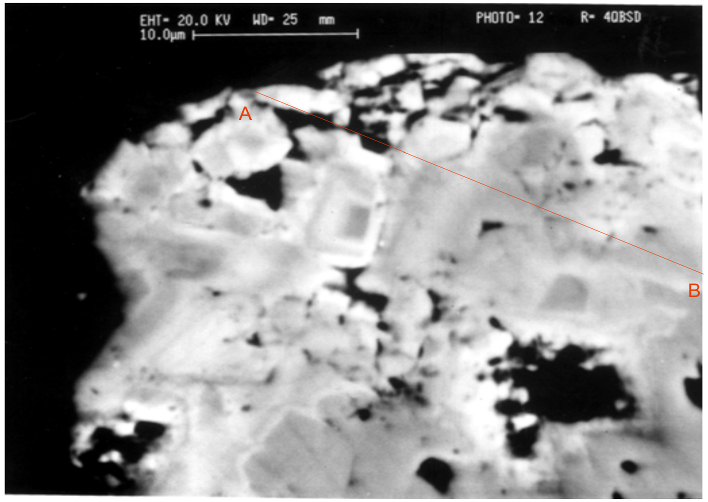
- Most deposits contain more than just the ore commodity such as gold or silver
- Often ore components such as zinc can be present in low concentration & cause metallurgical problems
- Environmental issues- As, Hg, Sb,Tl, Te… can have high treatment costs and be long term liability

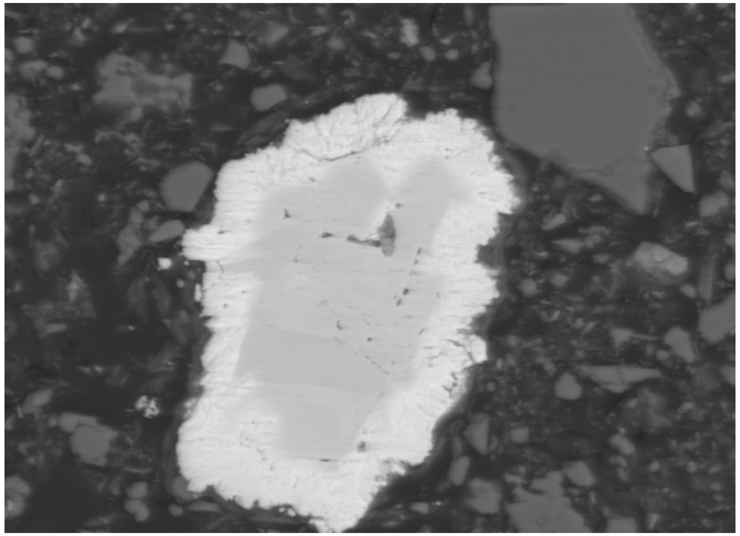
Precious metals as trace elements

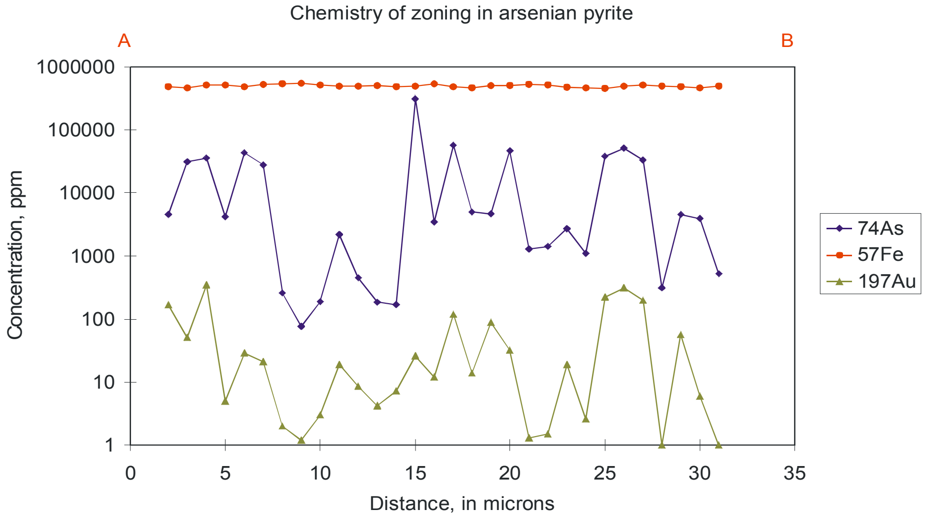
- Many elements of interest in mineral processing occur as trace components
- Identifying the mineral hosts critical to improving recovery or minimising impacts
- Move from diagnostic leaching to *in-situ* investigation
- Several analytical methods for *in-situ* trace element analysis
- Laser Ablation Inductively Coupled Plasma Mass Spectrometry is one of these methods



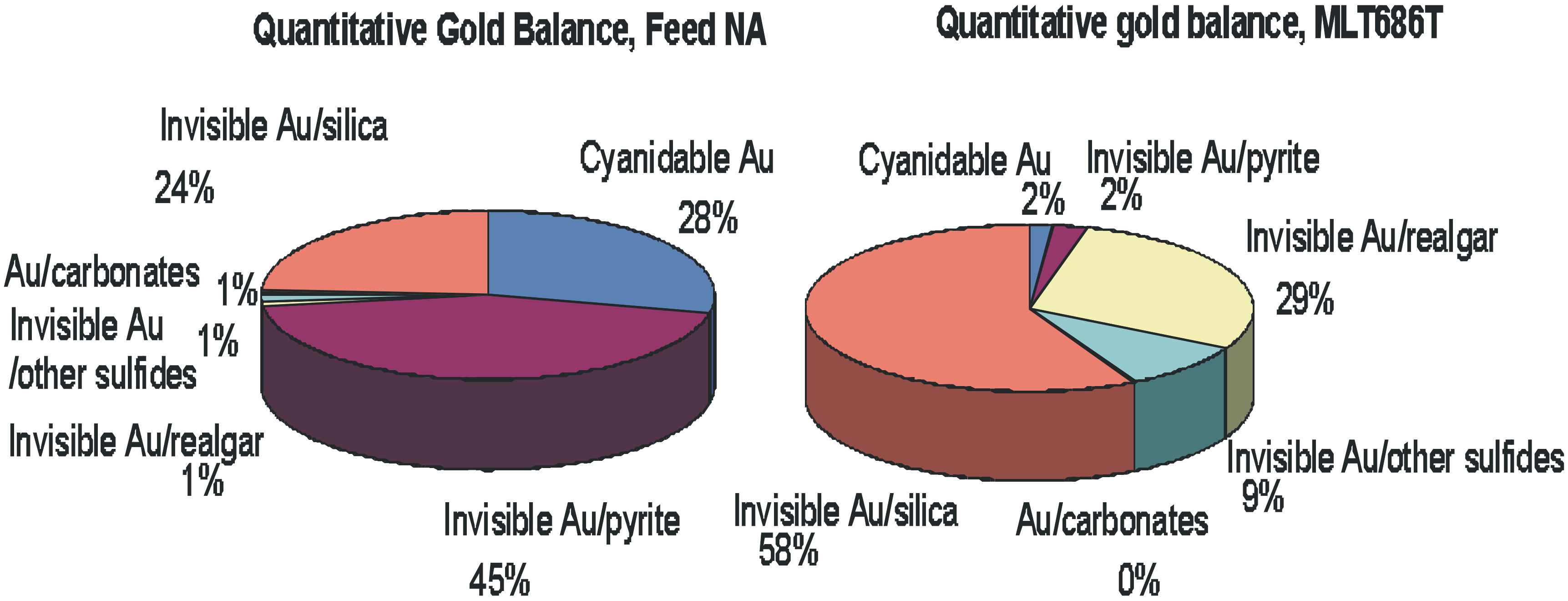
Gold-rich rim, arsenian pyrite



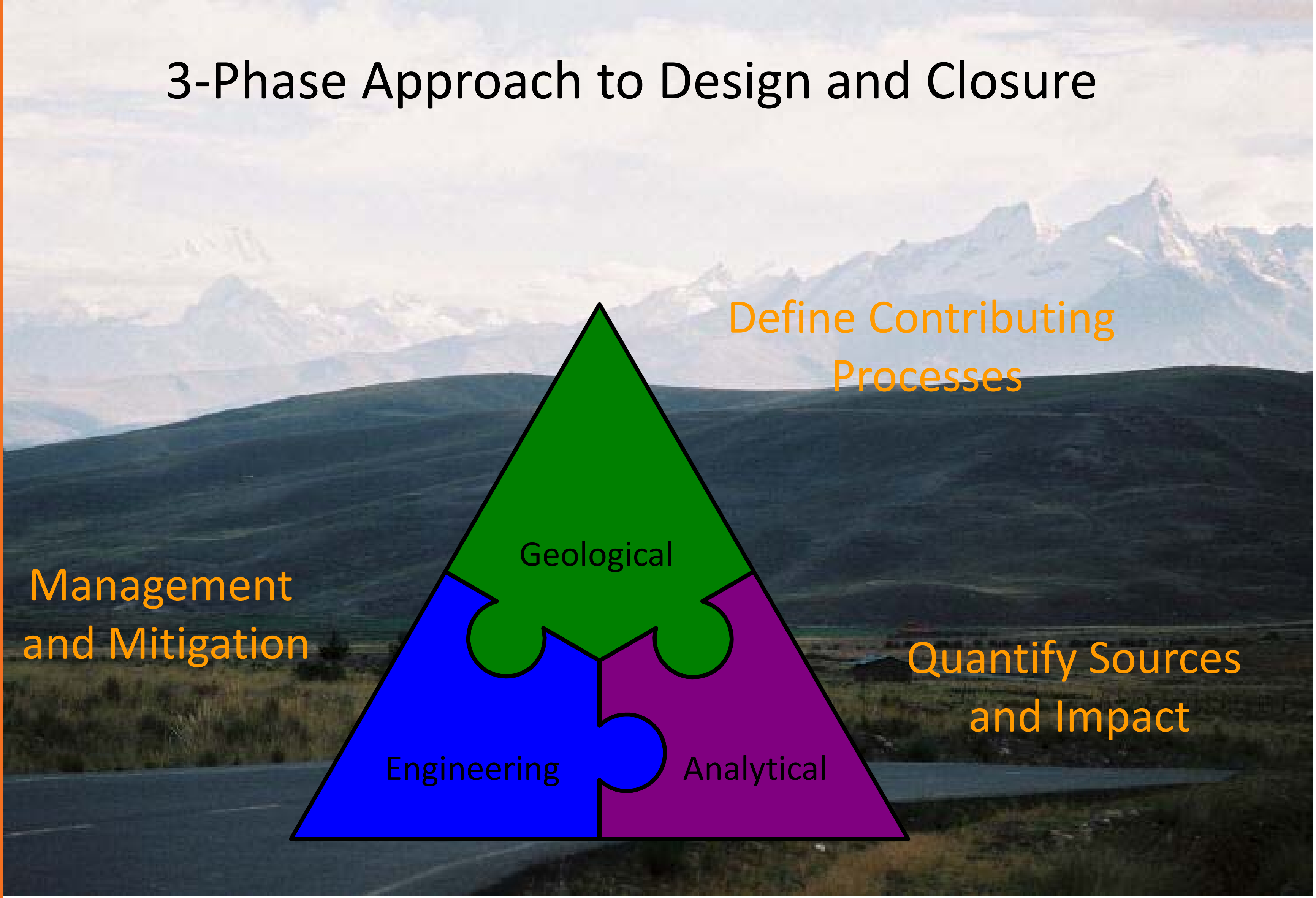




Gold in Autoclave Discharge



3-Phase Approach to Design and Closure



Geological

Define Contributing Processes

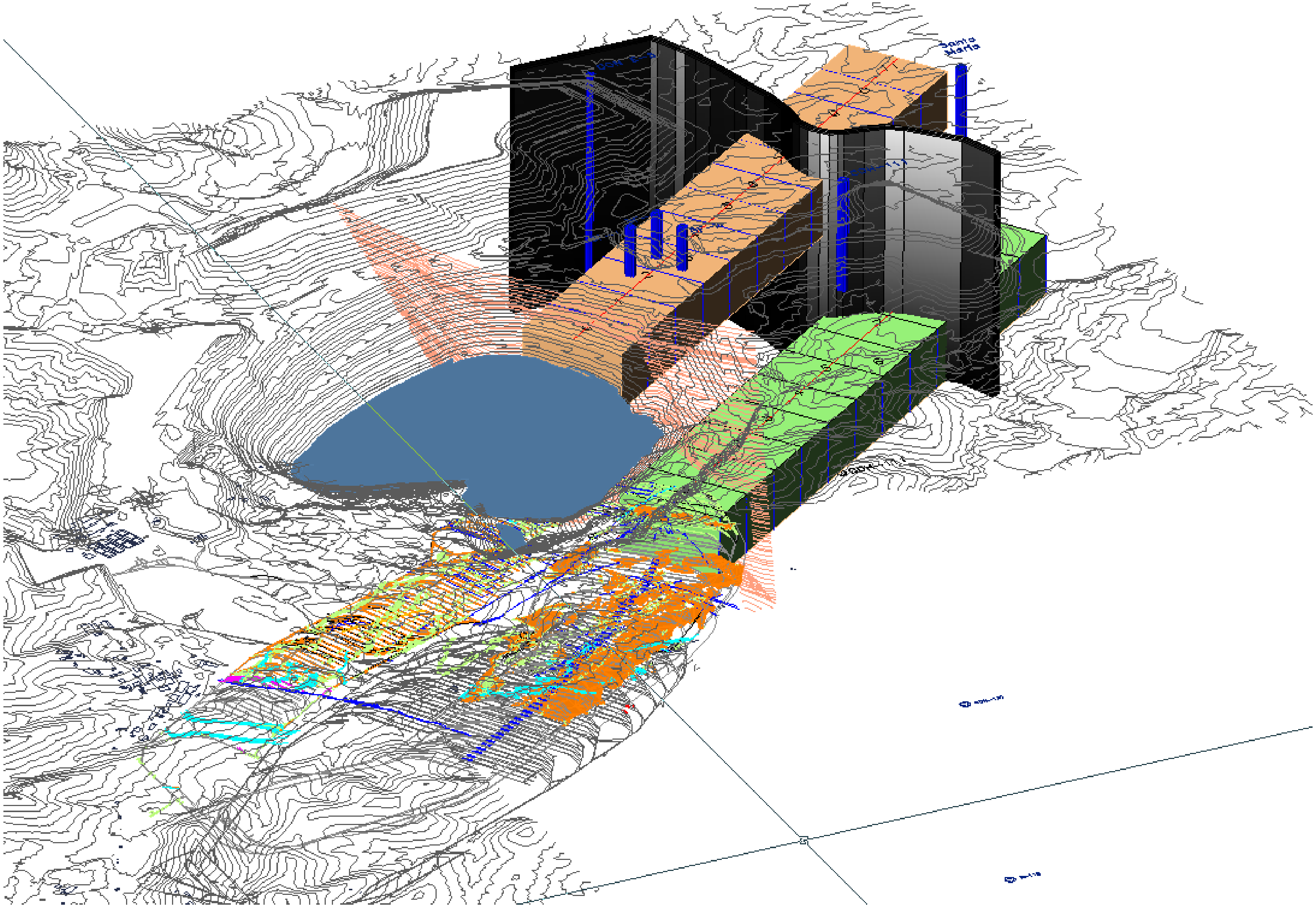
Analytical

Quantify Sources and Impact

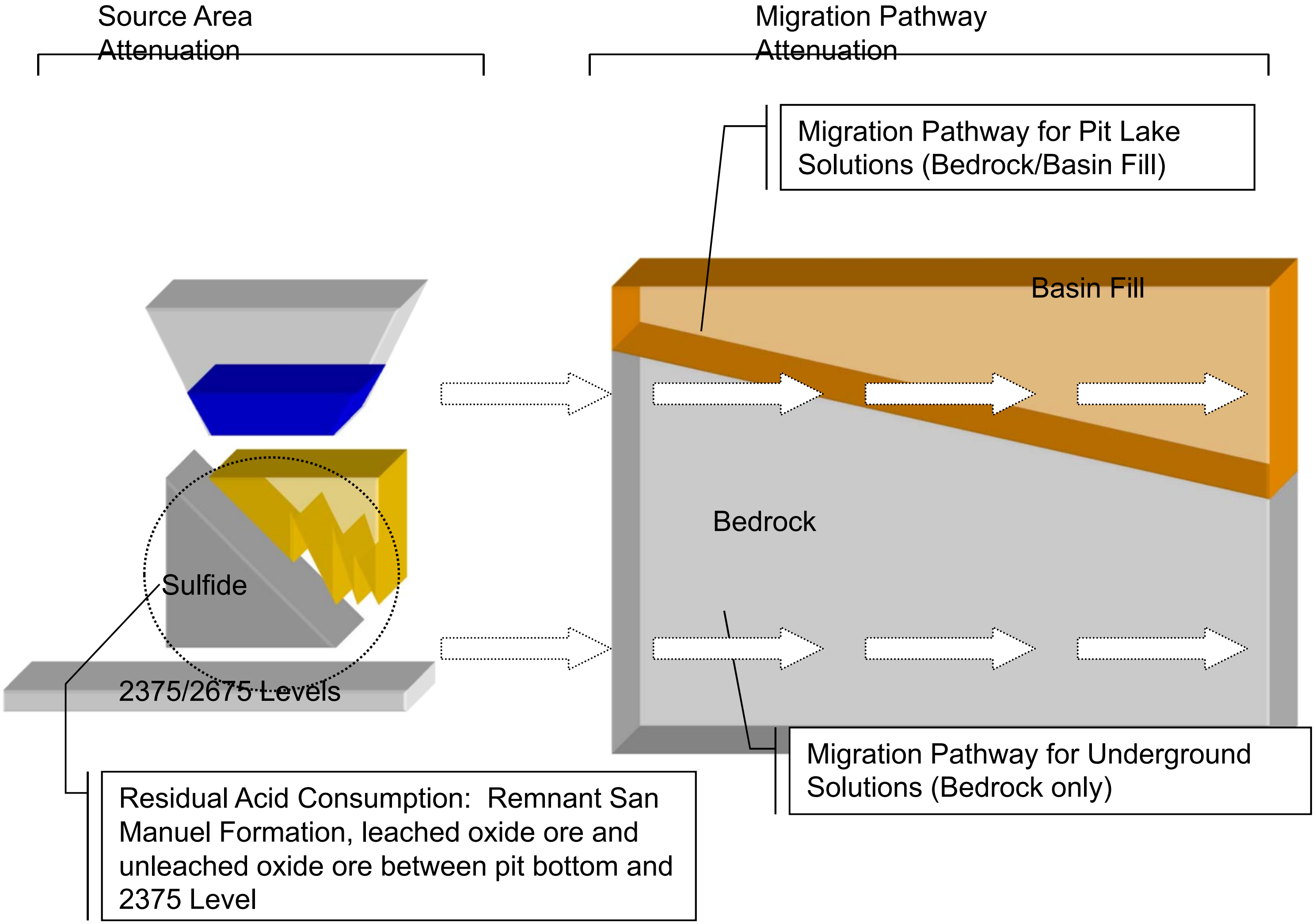
Engineering

Management and Mitigation

Groundwater Impacts



Containment & Attenuation



Migration Pathway for Pit Lake Solutions (Bedrock/Basin Fill)

Migration Pathway for Underground Solutions (Bedrock only)

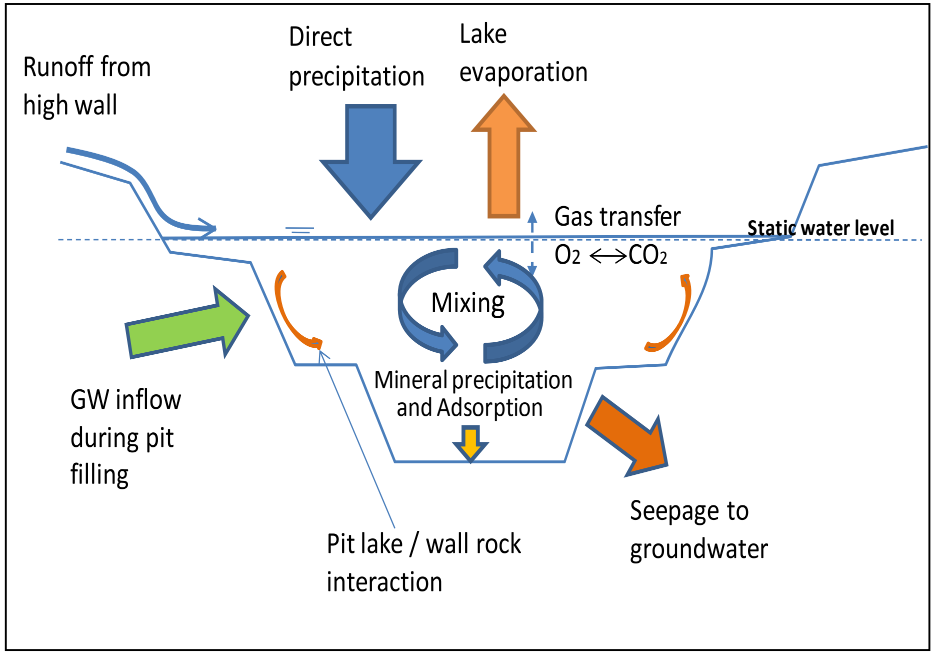
Residual Acid Consumption: Remnant San Manuel Formation, leached oxide ore and unleached oxide ore between pit bottom and 2375 Level

ISL circuits

- Attractive low cost mining
  - Typical ~$20/ton total costs
- Require specialized hydrogeologic conditions
- 12 operations to date
- 6 closed under development
- Potential to impact groundwater
- Aesthetic impacts low
- Critical geochemical issue- long term hydrogeochemistry in recovered field

Mine Pit Lakes

- Generally a closure issue
- Accumulation of water in abandoned pits
- Issues- poor water quality
  - Impact to groundwater
  - birdkills
- Terminal sink
  - Accumulation of metals, salts & acidity
  - Potential avian wildlife risk
- Through flow lake
  - Recharge
  - Impacts to groundwater
- Opportunities
  - Source of water



Surface Water Impacts

- Seasonally controlled
- Flow through system or terminal sink
- Seasonal flushing of salts, metals and acidity
- Loss of water quality
- Habitat and ecology loss
- Fish kills

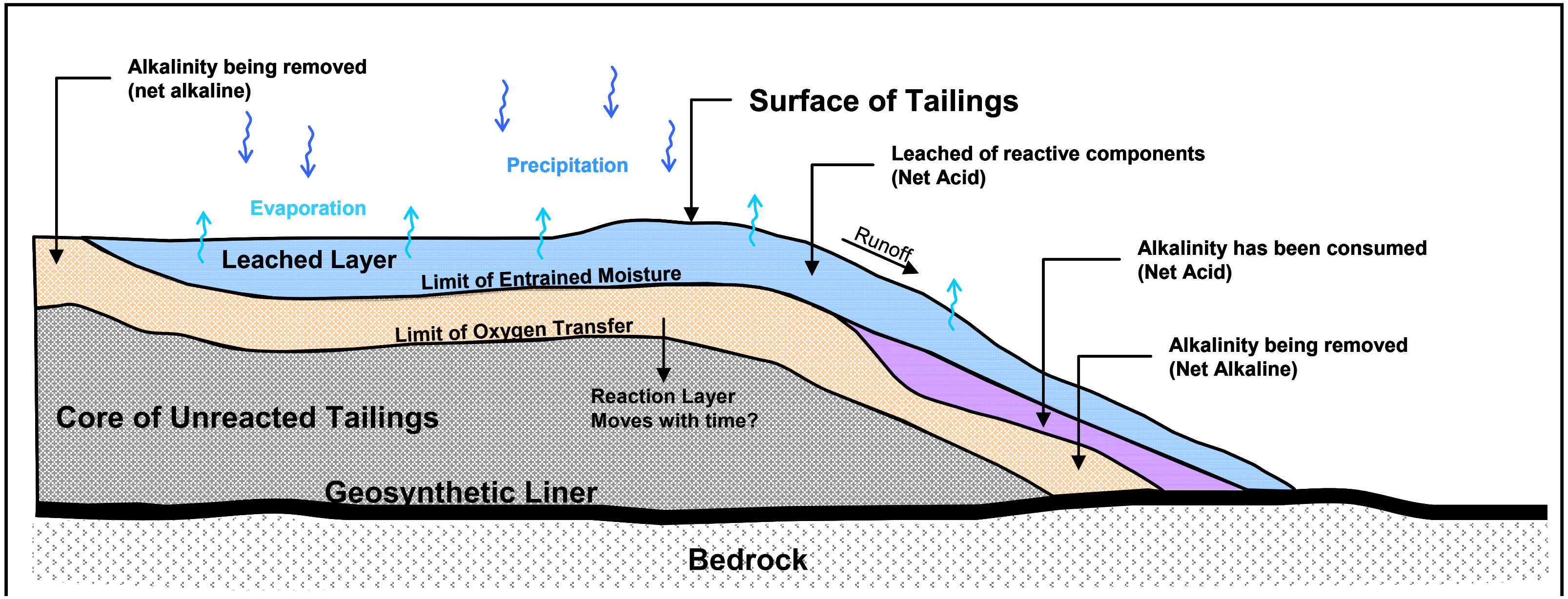
Waste Rock Facilities

- Sulfide oxidation in exposed waste rock
- Impact groundwater
- Impact surface water
- Wind blown solids from heap
- Physical stability – particularly with high clay material such as porphyry waste
- Long term geochemical changes
  - Cover versus left
  - Water management
  - Dust management

9/14/2000

Tailings

- Fine grained residual ore components
- High in metals
- Present potential impact to land by air dispersion
- Leaching potential impact to surface and groundwater



Example: San Manuel Tailings, Arizona

Tailings have a 44-year history.

No concentrations above AWQS at any down gradient well

Natural elevated fluoride in groundwater

Evidence of iron oxidation on dam outer face

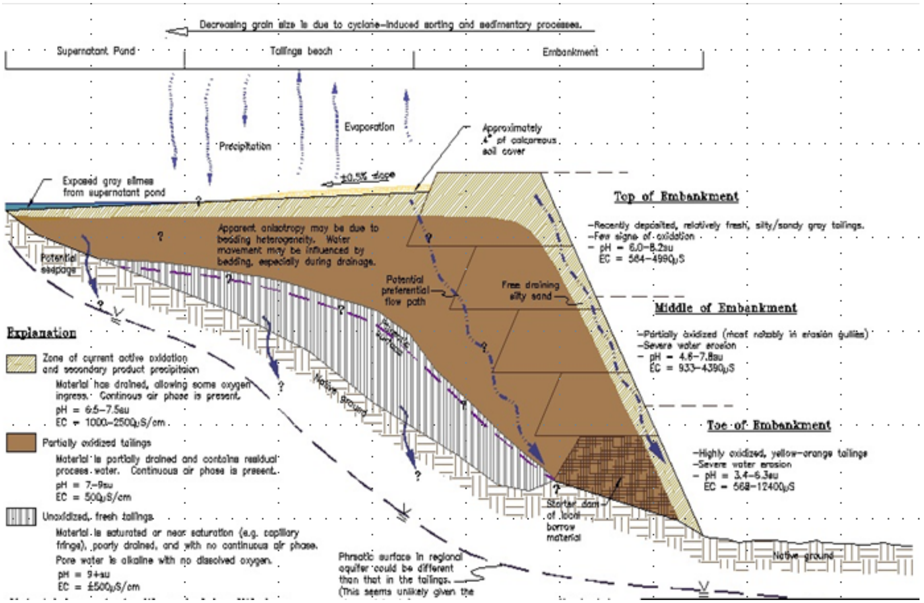
Little information on metal leaching, pre-2004

Previous work indicated non-acid generating, pre-2004

Observations on embankments indicated potential acid generation,

Seep at T#6, neutral pH, but trace Cd and SO_4 > 2,000 mg/L

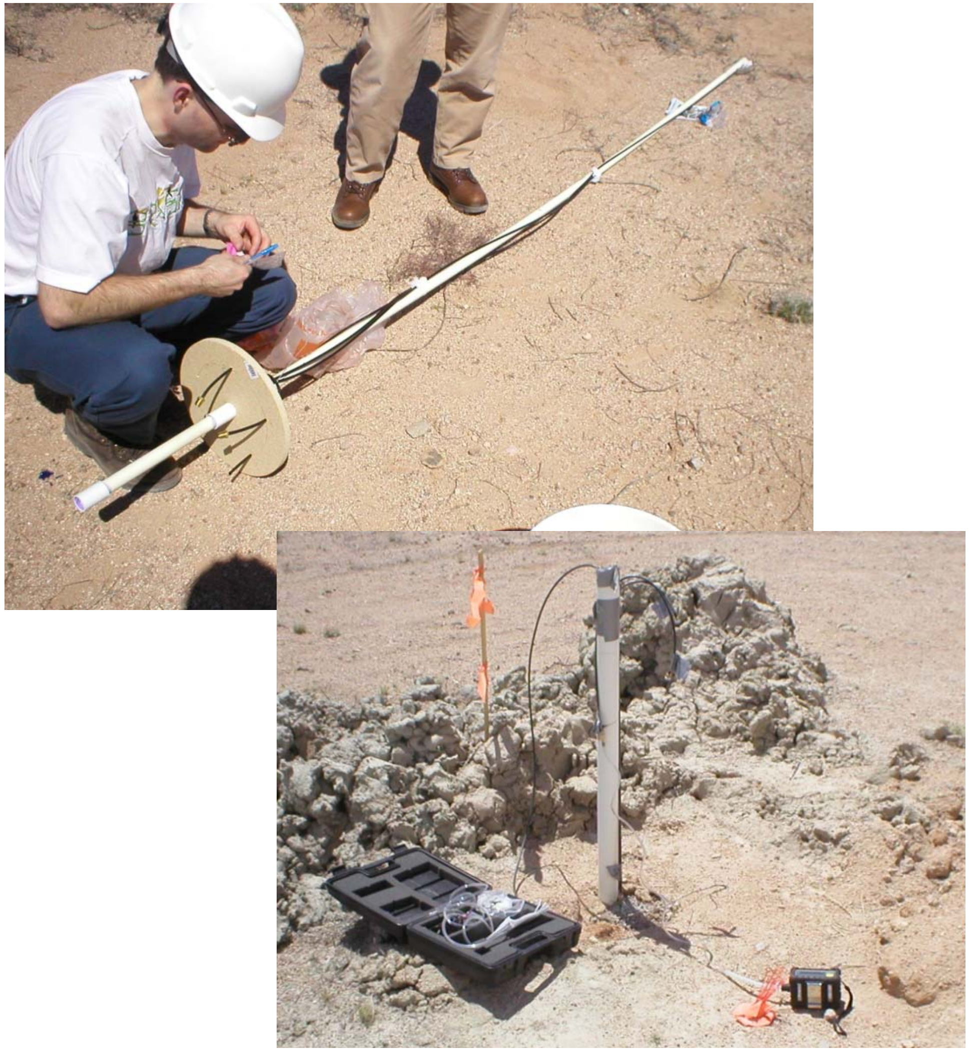
Need to investigate sub-surface tailings



Oxygen Distribution

- Estimate rate of O_2 ingress to tailings
- Oxygen drives sulfide oxidation
- Provide upper boundary for sulfide oxidation rate
- Critical to prediction of metal leaching as O_2 often rate limiting factor

$FeS_2 + O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+$



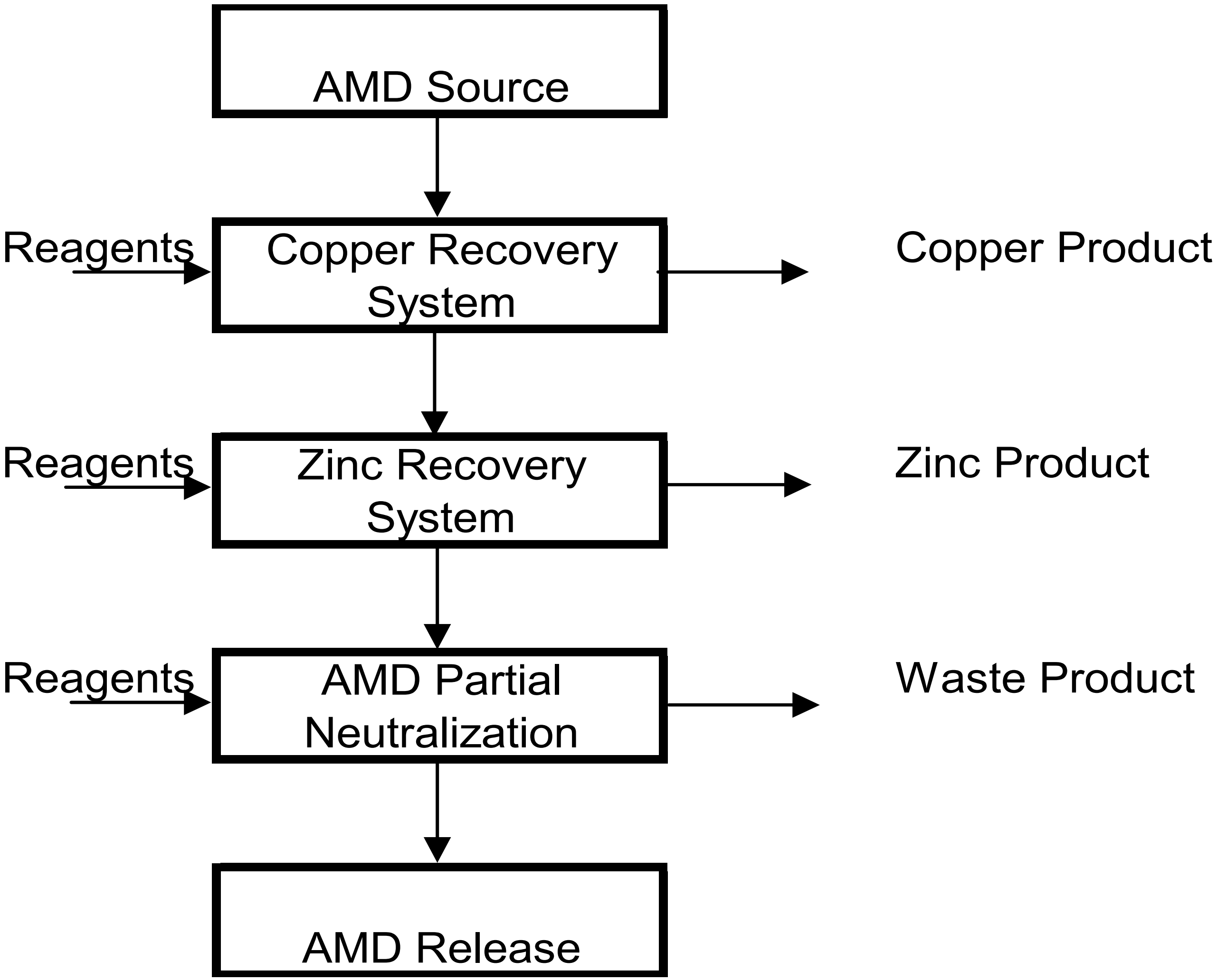
Geochemical Modelling: Oxygen

- Low flux of oxygen 10^{-4} to10^{-8} O_2 m^{-2} yr^{-1}
- Predicted pyrite oxidation rate, $<10^3$ moles FeS_2/m^3yr.
- Assuming contact, in tailings - pyrite oxidation
- O_2 transport rate is slow in basin tailings - limits pyrite oxidation
- Embankment > O_2 flux
- Oxygen throughout tailings - not rate controlling mechanism
- Cover system unlikely to reduce sulfide oxidation BUT would reduce moisture/water content

New Life in Old Mines?

- Precipitation methods
  - Metal precipitation using biogenic produced hydrogen sulfide (Bioteq)
  - Copper cementation
- Direct recovery methods
  - Direct electrowinning
- Direct solvent extraction and electrowinning
  - Resin or solvent chelation and recovery
  - Ion exchange recovery
  - MRT recovery
  - Combinations of the above e.g. two stage ion exchange involving chelation and solvent extraction principally for copper recovery
- All have pro's and con's dependent on water chemistry – same as any ore body

General process route



AMD Source

Reagents

Copper Recovery System

Copper Product

Reagents

Zinc Recovery System

Zinc Product

Reagents

AMD Partial Neutralization

Waste Product

AMD Release

Typical mine water chemistry

Parameter	Volcanogenic Massive Sulfide	High Sulfidation Epithermal	Mantos deposit	Porphyry	Copper SXEW (porphyry)
pH	<1-6	2-4	<2-6	2-8	<2
Cu	<0.1-6800	<0.01-5400	<0.01-790	<0.01-2100	~6000
Zn	<0.1->10000	<0.1-3900	<0.01-4300	<0.01-80	<500
Fe	10->10000	<1-28000	<1-5500	<0.01-1700	~2000
Pb	<1-165	<0.1-12	<1-210	<6	<100
Ag	<1-630	<1-90	<1-580	<2	~5

Summary Role of Geochemistry in Mine-Life Cycle

- Exploration
  - Deeper ores
  - Buried mineralization
- Mining/Metallurgy
  - Lower grades
  - Complex materials
  - Refractory ores
- Environment
  - More problematic elements
  - More complex waste
  - Stringent regulations
  - Social issues