The Role of Applied Geochemistry in the Mine-Life Cycle

SRK (UK): Rob Bowell

Date: September, 15, 2011
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

**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

**OPERATIONAL SUPPORT**
- QA - QC
- Chemical stability of rocks
- Hydrogeochemical monitoring
- Geometallurgy
- Waste Management

**MINE DEVELOPMENT**
- Resource Estimation
- Quantification
- QA - QC
- Environmental Assessment
- Geometallurgy

**GEOCHEMISTRY IN THE MINE - LIFE CYCLE**
• 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
Exploration under cover

- Glacial deposits
- Thick gravel and scree deposits
- Thick alluvium or colluvium + deep weathering
- Aeolian deposits
- Volcanic ash
- Ice
Sample selection

Distribution of Au, Mt Gibson and Boddington

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
- Water (US beer)
- MMI
- Guinness
- Ammonium acetate
- Na-pyro / H₂O₂
- Acetate + HOAc
- Enzyme Leach / H₂O₂
- Weak acidified NH₂OH
- EDTA / H⁺
- Regoleach
- Strong acidified NH₂OH
- HCl
- Aqua regia
- Mixed acids
- HF / fusion

Adsorbed & Exch. species
- Carbonates
- Mn-oxides & am. Fe-ox.
- Cryst. Fe-oxides
- Silicates
- Resistate minerals

Increasing age of mineral phase in regolith
Less transitory metal contents
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-HCO₃)
## Summary of risk reactor pathways

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

ALKALINITY

100%

ACIDITY

100%

% total as mg/l CaCO₃

%S (SO₄^{2-} + Cl⁻) meq/l

PUMPED DEEP GROUND WATERS

BRINES

NET ALKALINE

NET ACID

Carbonate Pb-Zn

Low Sulfidation

Clay pits

Porphyry

Porphry

High Sulfidation

Carlin

Shear zone Au

Low Sulfidation

High Sulfidation

Pumped Deep Ground Waters

Brines

Net Alkaline

Net Acid

Carbonate Pb-Zn

Low Sulfidation

Clay pits

Porphyry

Shear zone Au
Metal chemistry in drainage, Ficklin plot

![Ficklin plot showing metal chemistry in drainage](image)
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

AP vs NP - by tailings empoundment

Net Acidic

Net Neutralising

Zone of Low Reactivity

Uncertain
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+
Consumption of Neutralization Potential

Time (Weeks)

Neutralizing Potential (%)

T3_G4
T3_BH4_30
T3_BH4_10
T10_BH3_05
T10_BH1_220
T10_BH1_130
T10_BH1_7.5
T1_BH7_90
T1_BH7_50
T5_BH25_40
T6_BH24_20
T1_BH9_60, BH27_15
T5_BH25_50, BH12_50
T6_BH23_70
HCT Load Release: Sulfate

SO₄ Loads vs. Time - All Cells

Sulfate (mg/kg/week) vs. Time (Weeks)

- T3_G4
- T3_BH4_30
- T3_BH4_10
- T10_BH3_05
- T10_BH1_220
- T10_BH1_130
- T10_BH1_7.5
- T1_BH7_90
- T1_BH7_50
- T5_BH25_40
- T6_BH24_20
- T1_BH9_60, BH27_15
- T5_BH25_50, BH12_50
- T6_BH23_70

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Metals Speciation in Minerals

Pre HCT

Post HCT
Prediction of Future Geochemistry
Conceptual Evaluation of Tailings Geochemistry

- Precipitation
- Evaporation
- Gas Transfer
- Surface ponding
- Gas transfer
- Sulfide oxidation front
- Cyanide + metals in entrained decant waters
- Tailings drawdown and meteoric leaching
- Groundwater flow
- Lenses of CaCO₃
- Process Water CaO
- Formation of CaCO₃ Cement

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Groundwater Model Predictions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AWQS (mg/L)</th>
<th>Maximum (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antimony</td>
<td>0.006</td>
<td>0.0016</td>
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<tr>
<td>Beryllium</td>
<td>0.004</td>
<td>0.00060</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.005</td>
<td>0.0016</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.1</td>
<td>0.051</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.05</td>
<td>0.0046</td>
</tr>
<tr>
<td>Thallium</td>
<td>0.002</td>
<td>0.00013</td>
</tr>
</tbody>
</table>
Interpretation of TMF Geochemistry

- Alkalinity being removed (net alkaline)
- Evaporation
- Precipitation
- Leached of reactive components (Net Acid)
- Alkalinity has been consumed (Net Acid)
- Alkalinity being removed (Net Alkaline)
- Runoff

Core of Unreacted Tailings

Geosynthetic Liner

Bedrock

Limit of Entrained Moisture

Limit of Oxygen Transfer

Reaction Layer

Moves with time?
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 gastrointestinal 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 Requirements
Passive Attenuation

$$y = 0.1707\ln(x) + 0.1118$$
$$R^2 = 0.9217$$

$$y = 0.0405\ln(x) + 0.0234$$
$$R^2 = 0.8913$$

Element Release

Element Attenuation

Ratio of Effluent Concentration (C)/Influent Concentration (C₀)

Cumulative Liquid to Solid Ratio

Element Release

Element Attenuation

Cobalt
Nickel
Copper
Neutrality
Log. (Cobalt)
Log. (Nickel)
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°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

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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

- 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 Rock Management
- Site Water Chemistry
- Receiving Water Chemistry
- Impact Assessment
- Mine Plan
- Water Balance
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

ArSENIC Effective Diffusivity = 10^-9.56 cm^2/s
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

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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

Predicted Percent of Uranium Recovery in Time as Function of Productivity

- P=2kg/m²
- P=4kg/m²
- P=8kg/m²

Legend:

<table>
<thead>
<tr>
<th>ZONE</th>
<th>PERMEABILITY THICKNESS</th>
<th>URANIUM GRADE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZONE 1 HIGH</td>
<td>14.067</td>
<td>0.170</td>
</tr>
<tr>
<td>ZONE 1 LOW</td>
<td>16.207</td>
<td>0.192</td>
</tr>
<tr>
<td>ZONE 2 HIGH</td>
<td>19.406</td>
<td>0.175</td>
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<tr>
<td>ZONE 2 LOW</td>
<td>0.097</td>
<td>0.020</td>
</tr>
<tr>
<td>ZONE 3 HIGH</td>
<td>7.123</td>
<td>0.134</td>
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<tr>
<td>ZONE 3 LOW</td>
<td>5.862</td>
<td>0.052</td>
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<tr>
<td>ZONE 4</td>
<td>5.360</td>
<td>0.050</td>
</tr>
<tr>
<td>ZONE 5</td>
<td>1.232</td>
<td>0.020</td>
</tr>
</tbody>
</table>
Geochemical Predictions

Predicted Production for Life of operations

Total Production
SRK: 5,810,594 kg U

Uranium Produced (kg)

Year

Faleo-Channel 5  Faleo-Channel 6  Faleo-Channel 7  Faleo-Channel 3
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 $\text{UO}_2^{2+}$
- In Uranium minerals, uranium present in crystal lattice – most commonly as $\text{U}^{IV}$ – 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

Chemistry of zoning in arsenian pyrite

Concentration, ppm vs. Distance, in microns

Graph showing concentration of 74As, 57Fe, and 197Au along a profile A-B.
Gold in Autoclave Discharge

Quantitative Gold Balance, Feed NA
- Invisible Au/silica: 24%
- Cyanidable Au: 28%
- Au/carbonates: 1%
- Invisible Au/other sulfides: 1%
- Invisible Au/realgar: 1%

Quantitative gold balance, MLT688T
- Cyanidable Au: 2%
- Invisible Au/pyrite: 2%
- Invisible Au/silica: 58%
- Au/carbonates: 9%
- Invisible Au/realgar: 29%
- Invisible Au/other sulfides: 0%
3-Phase Approach to Design and Closure

Define Contributing Processes

Geological

Management and Mitigation

Quantify Sources and Impact

Engineering

Analytical
Groundwater Impacts
Containment & Attenuation

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

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
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 SO₄ > 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$_2$O = Fe$^{2+}$ + 2SO$_4^{2-}$ + 2H$^+$
Geochemical Modelling: Oxygen

- Low flux of oxygen $10^{-4}$ to $10^{-8}$ O$_2$ m$^{-2}$ yr$^{-1}$
- Predicted pyrite oxidation rate, $<10^3$ moles FeS$_2$/m$^3$ yr.
- 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
    - Reagents
    - Copper Product
  - Zinc Recovery System
    - Reagents
    - Zinc Product
  - AMD Partial Neutralization
    - Reagents
    - Waste Product
  - AMD Release
# Typical mine water chemistry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Volcanogenic Massive Sulfide</th>
<th>High Sulfidation Epithermal</th>
<th>Mantos deposit</th>
<th>Porphyry SXEW (porphyry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>&lt;1-6</td>
<td>2-4</td>
<td>&lt;2-6</td>
<td>2-8</td>
</tr>
<tr>
<td>Cu</td>
<td>&lt;0.1-6800</td>
<td>&lt;0.01-5400</td>
<td>&lt;0.01-790</td>
<td>&lt;0.01-2100</td>
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<td>Zn</td>
<td>&lt;0.1-&gt;10000</td>
<td>&lt;0.1-3900</td>
<td>&lt;0.01-4300</td>
<td>&lt;0.01-80</td>
</tr>
<tr>
<td>Fe</td>
<td>10-&gt;10000</td>
<td>&lt;1-28000</td>
<td>&lt;1-5500</td>
<td>&lt;0.01-1700</td>
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<tr>
<td>Pb</td>
<td>&lt;1-165</td>
<td>&lt;0.1-12</td>
<td>&lt;1-210</td>
<td>&lt;6</td>
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<tr>
<td>Ag</td>
<td>&lt;1-630</td>
<td>&lt;1-90</td>
<td>&lt;1-580</td>
<td>&lt;2</td>
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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