Mine drainage: geochemistry, impact and management

Short Course SC2: AusIMM Conference 2011
# Programme

31 August 2011

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
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<tr>
<td>8:45 - 9:00</td>
<td>Assemble - coffee</td>
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<tr>
<td>9:00 - 9:30</td>
<td>Introduction</td>
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<td>Dave Trumm</td>
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<td>9:30 - 10:15</td>
<td>Introduction to mine drainage geochemistry</td>
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<td>James Pope</td>
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<td>10:15 - 10:30</td>
<td>Morning Tea</td>
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<td>10:30 - 11:30</td>
<td>Coal mine drainage geochemistry</td>
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<td>11:30 - 12:30</td>
<td>Gold mine drainage geochemistry</td>
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<td>12:30 - 1:00</td>
<td>Lunch Provided</td>
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<td>1:00 - 2:00</td>
<td>Biological impacts</td>
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<td>Jo Cavanagh/Duncan Gray</td>
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<td>2:00 - 3:00</td>
<td>Remediation</td>
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<td>3:00 - 3:15</td>
<td>Afternoon Tea</td>
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<td>3:15 - 4:00</td>
<td>Regulatory and framework</td>
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<td>Jo Cavanagh</td>
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<td>4:00 - 4:40</td>
<td>Summary and Wrap up</td>
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<td>Dave Trumm</td>
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Introduction

• Why do we have a mine drainage programme?

• How does the programme work?

• The case study
Why do we have a mine drainage programme?

West Coast & Southland

- Long history of coal and gold mining
  - 3 million tonnes/annum coal
  - 75,000 ounces gold/annum
- Potential for substantial expansion of these high-value export commodities
- Several new companies currently doing advanced exploration in both coal and gold

West Coast coal

Main resource: high quality steel-making coal
(highest quality coking coal in world)
2 million tonnes/year exported

At least 3 new large mines planned in near future

Note: specialist coal with negligible use for local energy production
West Coast gold
One major open cut mine in current operation
Current deep drilling: two potential underground mines
Three companies doing active exploration elsewhere

Southland coal: mainly lignite
Advanced investigation for large-scale energy utilisation

Alluvial gold
Mainly in Quaternary gravels
Many small operations: 30,000 ounces/annum
Short-lived (1-5 years); move plant to new site
History

• 1970s - Mine drainage chemistry recognised

• 1980s & 1990s - Environmental awareness developed

• Prediction and management tools developed in USA, Canada, Europe and Australia

• NZ - Limited government investment in mining related environmental research - 1980s and 1990s
  • Universities (Auckland, Canterbury and Otago)
  • Regional Councils
  • Consultants
  • Mining Companies
Result

- Increased environmental awareness of mining issues
  - Many local examples of poor water quality from historic mines
  - Some failures - Tui Mine

- Limited New Zealand data or expertise
  - Geological
  - Geochemical
  - Biological
  - Management

- International research and practices have moved on so that mine drainage becomes a management issue elsewhere

Lack of common ground

- Regional councils and DoC expected to have expertise/policy in mine drainage management

- Mining companies preparing consent applications with little background data

- Consent delays
  - Pike River
    - Applications made, appealed twice, granted
    - At least 7 years to consent (mid 90s – 2000s)
  - Globe Progress

- Why develop a Framework...
  - It’s at least 10y overdue
How does the programme work?

- Will a proposed mine make acid or release trace elements?
- What is the likely impact?
- Can it be fixed or prevented?

Research team.....

- Geology and Geochemistry
- Freshwater biology & ecotoxicology
- Management and treatment
- Policy and Regulation
Research programme structure

Research Team

Governance Panel

West Coast RC
Environment Southland
Dept of Conservation
Solid Energy
Oceania Gold
Coal Association
Minerals West Coast

Our approach

• Compile background information and define gaps
• Establish predictive relationships
  • Geology → Mine drainage
  • Impacted water quality → Aquatic ecology
  • Mine drainage → Treatment systems
• Develop the Framework in consultation with industry and regulators

Research outputs

Workshops

Peer reviewed publications

Local/international conferences

Coal Mine Drainage Geochemistry, West Coast
South Island – a Preliminary Water Quality Impact
Model

Research outputs

Population science articles

Coal mine drainage: Complex effects on streams

Abstract

Predicting the effects of coal mines on aquatic environments

Fliers

Prepared environmental impacts on streams from mining

Treatments of acid and pristine streams using the UMB→free charts for New Zealand conditions

8
Framework

1. Proposed operations
2. What is the potential for a detrimental ecological impact?
3. What is the level of potential impact?
4. Yes
   - Proceed (with ongoing monitoring)
5. No
   - How do we reduce impact to an ‘acceptable’ level?
6. Operational Management
7. Treatment during operation
8. Decision-making step

Step by Step Guide

1. Collate background info (geology, receiving streams)
2. Collect rock samples for ABA
3. Analyse samples
4. Predict mine drainage chemistry
5. Predict water chemistry after mixing with receiving stream
6. Determine ecological impact
7. Consider whether impacts are acceptable
   7a. Decide on management / remediation techniques
8. Decide monitoring programme

Case study
General Scenario

- 20 MT lignite mine
- Covers approx 45 km²
- Only 4km x 1km open at a time
- Water from pit discharged to stream, 90 m³/day
- Pits backfilled with waste rock

Stage 1: southern end of mine, lignite mining

Stage 2: commences approximately 10 yrs after stage 1, lignite mining

Stage 3: Gold-dredgings indicate extractable gold, gold mining prior to lignite mining

Background Data

- Exploratory drilling and preliminary assessment has been undertaken
- The results of drilling for each stage are available
- Receiving streams pristine
- Further assessment is required to assist in resource consent application
Introduction to Mine Drainage Geochemistry

Contents

• Description of mine drainage chemistry
• Typical acid mine drainage chemical reactions
• Geochemistry immediately downstream of the AMD formation zone
• Methods of Prediction
  — Geological correlations
  — Analogy
  — Acid base accounting
  — Kinetic testing
• The Framework

Take Home Messages

• Mine drainage chemistry is highly variable, and evolves in time and space
• Understanding of key and common mine drainage chemical reactions
• Mine drainage formation environment is a separate geochemical system to the downstream environment
• Mine drainage chemistry is predictable using different methods to different levels of certainty
Description of chemistry

• Geochemical properties are extremely variable
  – pH measured from -2 (AMD, Iron Mtn US) to 13 (Bauxite refinery residue, Gladstone, Aust.)
  – Highly acidic (elevated dissolved Al, Fe, Mn etc) to highly alkaline (elevated HCO$_3^-$), high OH$^-$$^-$ in bauxite refinery residue
  – Extremely oxidised to extremely reduced
  – Trace elements range from unchanged from background to enriched by several orders of magnitude

Eh-pH Range for mine drainages

Controls on mine drainage chemistry

• Geology
  – Fundamentally controls the mineralogy of rocks
  – Deposit type

• Environment
  – Climate, amount and intensity of rainfall, temperature, humidity
  – Topography

• Mine type and mining processes
  – Influences the grain size and reactive surface area of rocks disturbed by mining
  – Hydrogeology

• Time
  – Mine drainage chemistry evolves with time
• Example of chemical variability
• Same mine site, similar rock types
• Similar concentration distribution for most components

From McCauley et al 2010

Important chemical reactions

1. \( \text{FeS}_2 + 3.5 \text{O}_2 + \text{H}_2\text{O} = \text{Fe}^{2+} + 2\text{SO}_4^{2-} + 2\text{H}^+ \)
   \( \text{Dissolution of FeS}_2 \) and oxidation of S to \( \text{SO}_4^{2-} \) by oxygen
   \( \text{Acid producing} \)

2. \( \text{Fe}^{2+} + \text{H}^+ + 0.25 \text{O}_2 = \text{Fe}^{3+} + 0.5 \text{H}_2\text{O} \)
   \( \text{Oxidation of FeII to FeIII by oxygen} \)
   \( \text{Acid neutralising} \)
   \( \text{Relatively slow} \)

3. \( \text{Fe}^{3+} + 3 \text{H}_2\text{O} = \text{Fe(OH)}_3 + 3\text{H}^+ \)
   \( \text{Complete hydrolysis of FeIII and precipitation of ferrihydrite} \)
   \( \text{Acid producing} \)
   \( \text{Intermediate precipitates, jarosite, schwertmannite are common} \)

Reactions continued

4. \( \text{FeS}_2 + 3.75 \text{O}_2 + 3.5 \text{H}_2\text{O} = \text{Fe(OH)}_3 + 2 \text{H}_2\text{SO}_4 \)
   \( \text{Summary reaction} \)
   \( 1 \text{ mole of FeS}_2 = 2 \text{ moles of H}_2\text{SO}_4 \)

5. \( \text{FeS}_2 + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} = 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 16\text{H}^+ \)
   \( \text{Oxidation of pyrite by dissolved FeIII} \)
   \( \text{At low pH Fe hydrolysis (eqn 3 previous slide) does not occur and FeII can stay in solution} \)

6. \( \text{KFe}_3[\text{OH}]_6[\text{SO}_4]_2 + 3\text{H}_2\text{O} = 3\text{Fe(OH)}_3 + \text{K}^+ + 2\text{SO}_4^{2-} + 3\text{H}^+ \)
   \( \text{Dissolution of jarosite} \)
   \( \text{Release of stored acidity} \)
Rate of pyrite oxidation reaction

- Rate limiting step is oxidation of FeII to FeIII

![Graph showing the rate of pyrite oxidation reaction vs pH]

Stumm and Morgan 1996

Microbial catalysis

- Microbial activity increases the rate of reaction by $10^6$

![Graph showing the influence of pH on microbial activity]

Evangelou 1998

Field data on Fell oxidation rate

![Graph showing field data on Fell oxidation rate vs pH]

Williamson et al 2006
Changes in chemistry with time

- Little published data from New Zealand
- In general an acid forming rock will produce acid at a maximum rate shortly after exposure to water and oxygen then acid production will decrease with time
  - Exact shape is highly variable and relates to Acid base accounting
- In general kinetic test data from BCM indicates
  - Peak acid rate of production occurs relatively quickly if no ANC
  - Trace elements generally peak before peak acid release
- Can expect that relatively stable AMD composition will occur while mine is operational
  - Waste rock replenished

Other chemical considerations

- Trace elements can occur in pyrite up to several weight %
- Acid formed by pyrite oxidation reacts with other components in the rock to release other metals and trace elements such as Al and Mn
- Some sulphide minerals do not release acid when they dissolve
  - Insufficient concentrations of transition metal to hydrolyse eg...
    - $\text{Zn} + \text{H}_2\text{O} \rightarrow \text{Zn(OH)}_2 + \text{H}_2$   

Summary

- Mine drainage chemistry is variable, relates to nature of mineral deposits, environment, mining process etc.
- In typical AMD pyrite is the main source of acid and other sulphides contribute some acid and trace elements
- The AMD forming reactions are stepwise and there are intermediate products
- Microbial processes and secondary reactions with FeIII as an oxidant are important at low pH
Chemistry immediately down stream

- Not simply dilution – reactive components released by AMD forming processes
- Downstream processes include
  - Dilution
  - Dissolution
  - Neutralisation
  - Precipitation
  - Adsorption
- Geochemical/mineralogical facies can be identified
- The downstream environment is a separate geochemical system to the AMD forming environment

Facies

- Three recognised facies (España 2006)
  - FeII rich (anoxic)
  - FeIII rich (suboxic)
  - Aluminous (oxic)
- Size of each is varies with seep chemistry
- Reactions in each facies have different implications for trace elements
- Also identify mineralogical control of Fe and Al in different pH zones
  - pH ~ 2: Jarosite
  - pH 2 – 4: Schwertmannite
  - pH 4 – 5: Basaluminite
  - pH >6: Ferrihydrite

Dissolution

- Feldspar breakdown is common
- \[ \text{KAlSi}_3\text{O}_8\text{(s)} + 10\text{H}_2\text{O} + 3\text{Fe}^{3+} \rightarrow 2\text{SO}_4^{2-} \]
- \[ \rightarrow \text{KFe}_2(\text{SO}_4)_2\cdot(\text{OH})_6\text{(s)} + 3\text{H}_2\text{SiO}_3\text{+} + 2\text{H}^+ + \text{Al}^{3+} \]
- Incongruent dissolution of potassium feldspar to form jarosite
- Release of acid
- Release of Al
Neutralisation and precipitation

- High Alkalinity
- Low pH, high Al
- Mixing Zone
- Alkalinity consumed
- pH increase
- Al(OH)₃ precipitation
- pH decrease

- Bicarbonate reacts with H⁺ to form CO₂
- Assumes an open system and escape of CO₂
- CaCO₃ is the most common source of HCO₃⁻

- Aluminium hydrolyses to and releases acid
- Many other possible Al minerals
  - Boemit: AlOOH
  - Alunite: KFe₃(SO₄)₂(OH)₆
  - Jurbante: Al₃(SO₄)₂

Precipitation of Al(OH)₃ in a stream

- Amorphous Al(OH)₃ 25°C
- Microcrystalline Gibbsite 35°C, 25°C & 15°C
Mine drainage titration

Trace elements

• Adsorption

Summary

• Downstream environment is a separate geochemical system to the AMD forming environment

• Most important processes are
  – Dilution
  – Dissolution
  – Neutralisation
  – Precipitation
  – Adsorption

• Implications are important for management of mine drainage, interpretation of sample data and prediction of downstream biological impacts
Prediction methods

1. Environmental Geology
2. Analogy with similar mines in similar geological and physiographic environments
3. Static testing = Acid Base Accounting
4. Kinetic Testing = field or laboratory based leach tests

Environmental Geology – Regional Scale

- Regional scale - geological control of mineralogy of deposit host rocks
  - Depositional environment
  - Diagenetic history
  - Provenance
  - Primary magmatic composition
  - Subsequent alteration

Regional Geology
Environmental Geology – Deposit Scale

- Identification of control of environmentally significant minerals eg FeS₂, CaCO₃
  - Rock type relationships
  - Bedding relationships
  - Roof and floors of coal seams
  - Shell horizons
  - Mineralogy of alteration zones
  - Distribution of alteration zones
  - Grain size / reactivity of minerals

Analogy

- AMD composition can be predicted by comparison to similar mines in similar rock types
- Important to identify an appropriate site for comparison
- Best to consider a range of conservative values

From McCauley et al 2010

Acid Base Accounting (ABA)

- Standardised laboratory tests to identify acid forming or neutralising capacity
- Define the presence or absence and relative abundance of acid forming or neutralising minerals
- Do not indicate chemistry of mine drainage
- Do not readily indicate the rate at which acid or alkalinity will be released
- Units are commonly kg(H₂SO₄)/t or kg(CaCO₃)/t of rock
  - Can use either units for acid neutralising or acid forming potential
  - Best to stick with one unit – I prefer kg(H₂SO₄)/t
  - Related through mass formulae
    - 98 kg(H₂SO₄)/t ~ 100 kg(CaCO₃)/t
ABA Tests

- **Maximum potential acidity (MPA)**
  - Usually based on total S
  - Assumes all S is FeS
  - Main interferences are non pyritic S which does not produce acid
    - Organic S
    - Sulphate S
    - Non acid forming sulphide S
  - Conservative

- **Acid Neutralising Capacity (ANC)**
  - Reacts sample with known amount of concentrated acid and then titrates back
  - Targets carbonates but there are other long term sources of neutralising capacity

- **Net Acid Generation (NAG)**
  - Measure NAG pH and NAG acidity (kgH$_2$SO$_4$/t)
  - Deduces sample and allows acid formed to react with carbonates
  - Interferences include organic material

- **Paste pH**
  - Only measures soluble acidity
    - Hydrolysable Fe
    - Soluble sulphate minerals
    - Adsorbed H$^+$

ABA Interpretation

<table>
<thead>
<tr>
<th>NAPP (MPA-ANC)</th>
<th>NAG</th>
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<tbody>
<tr>
<td>&gt; 10 kgH$_2$SO$_4$/t</td>
<td>Highly acid producing</td>
</tr>
<tr>
<td>1-10 kgH$_2$SO$_4$/t</td>
<td>Moderately acid producing</td>
</tr>
<tr>
<td>0-1 kgH$_2$SO$_4$/t</td>
<td>Low - no acid producing</td>
</tr>
<tr>
<td>&lt; 0 kgH$_2$SO$_4$/t</td>
<td>Low - no acid neutralising</td>
</tr>
<tr>
<td>1-10 kgH$_2$SO$_4$/t</td>
<td>Moderately acid neutralising</td>
</tr>
<tr>
<td>&lt; 1-10 kgH$_2$SO$_4$/t</td>
<td>Highly acid neutralising</td>
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ABA extended

- Some times extended ABA tests are used
  - Analysis of the reaction liquor from NAG or ANC
  - Monitoring rates of pH change in NAG
- Often development of field portable tests are important
  - past pH
  - Carbonate bomb
  - Field portable XRF
- Field tests are powerful when correlated with at good database of standard ABA data.
  - Deposit scale ratio of NAF vs PAF rocks
  - For example - Assuming PAF rocks are managed well, what is long term outlook for low PAF and NAF rocks remaining.

Kinetic Tests

- Commonly set up to collect leachate from rocks as they weather
- Can be field or laboratory based
- Can be used for many purposes, commonly
  - Predicting mine drainage chemistry in detail
  - Identifying mine drainage evolution trends
  - Trialling remediation or management strategies
  - Identifying leachable acidity compared to maximum potential acidity from ABA

Kinetic Tests

- Humidity cell
  - ASTM method
  - Internationally recognised
  - Identify relative rate of acid production/neutralisation, correlate with larger scale
  - Comparable with international results
- Column Leach
  - Standardised method AMIRA (Smart et al 2000)
  - Commonly used easy to set up
  - Identify relative rate of acid production/neutralisation, correlate with larger scale
  - Comparable between studies
- Field Columns/lysimeters
  - Site specific
  - Identify actual rate of acid production/neutralisation
  - Grain size and dump morphology not replicated
- Leach Pads
  - Site Specific
  - Variable size
  - Can replicate grain size and dump morphology
Kinetic Tests

- Limitations of kinetic testing
  - Increasing acidity
  - Decreasing oxygen and dissolved oxygen
  - Draffing if capped
  - Increasing reaction with other minerals
  - Modern dumps layered to reduce water and air infiltration
  - More complex to relate to kinetic test data

Column leach test apparatus

Framework

- Our Framework document assists with understanding of mine drainage geochemistry
  - Provides introduction to mine drainage geochemistry
  - Provides an introduction to analysis methods and a generic approach to their application and interpretation
    - Once site-specific data is collected there will be ways to improve on the generic approach
  - Provides a source of references
  - Provides some region-specific data and background information
- However
  - Not written to be a text book on any of the topics covered
  - All information is presented in the context of compiling data for resource consent
    - Approaches to data collection and interpretation will change in other phases of mine operation.
West Coast and Southland
Coal Mine Drainage
James Pope

Contents
1. Coal measures and host rocks
2. Coal mine drainage chemistry
   - Controls
   - Characteristics
   - Trace elements
3. Rock geochemistry
   - Acid base accounting
   - Kinetic and other testing
4. Implications for downstream
5. Case study

Coal Measures
- At a regional scale we correlate coal measures sequences with mine drainage chemistry
- Relationships are based on the assumption that the geological processes that define the different groups of coal measures also control the mineralogy of the coal measures
  - Tectonic regime
  - Provenance
  - Depositional environment
  - Diagenetic processes (what happens after burial)
Coal measures on the West Coast

- Brunner Coal Measures
  - Eocene
  - Delta to Estuary
  - Provenance
    - Granite
    - Greenland Gp
  - Transgression sequence above

- Paparoa Coal Measures
  - Cretaceous
  - Alluvial to Lucustrine
  - Provenance
    - Granite
    - Greenland Gp
    - Schist
  - Unconformity above

Coal measures in Southland

- Morley Coal Measures
  - Cretaceous
  - Alluvial
  - Provenance
    - Igneous (volcanic & plutonic)
    - Metamorphic
  - Regression

- Gore Lignite Measures
  - Miocene
  - Delta plain
  - Provenance
    - Otago Schist
    - Murihiku Rocks
    - Maco Coal Measures
  - Regression

Coal Measures

- Other coal measures in NZ
  - Beaumont (Southland)
  - Taratu Formation (Otago)
  - Waikato
  - Maryville (Taranaki)

- Relationships between regional geology and mine drainage geochemistry are a guide only and are no replacement for a site specific analysis
Coal mine drainage chemistry

- What do we want to know about our mine drainages?
  - Acid (AMD) or non-acid (NMD)
    - If yes, Fe rich or Al rich
  - Trace element enriched or not
    - If yes, which ones and what concentrations
  - Oxidised or reduced
    - DO, FeII:FeIII
  - Are there regional patterns that have predictive value?

Acidity in South Island coal mine drainages

Neutral mine drainages

- Have regional data with trace element analyses
  - Trace element concentrations measured to date are low
- Fe concentrations up to 12 ppm
- Al concentrations < 0.4
- pH typically > 5
- Alkalinity >70 ppm
Neutral mine drainages

Fe in neutral mine drainages

- At pH > 5 Fe(III) is insoluble, so how do we get up to 12ppm Fe in filtered samples?

Fe in neutral mine drainages

- Fe in these seeps is Fe(II) and ultrafine particulate Fe(III)
Summary

• Neutral mine drainages
  – Are relatively benign for trace elements but can have elevated Fe as FeII and colloidal Fe

• Acid mine drainages
  – Are enriched up to about 5 orders of magnitude above background for some components
  – Total acidity is not related to mine type
  – Correlation between rock types and acidity
    • Mudstone dominated mine waste produces more acidic seeps
  – Mine type influences the mine drainage chemistry
    • Al:Fe higher in open cast mine drainages
  – Trace elements higher from open case mines and appear to be from sulphide minerals

Coal measures geochemistry

• Approach
  – Use standard acid base accounting tests
  – Obtain a regional data set for coal measures
  – Investigate relationships between the acid base accounting geochemistry and geology

Acid mine drainages trace elements
Acid Base Accounting BCM

Net acid producing potential vs NAG acidity

Rock Geochemistry
Acidity in South Island coal mine drainages

Geochemistry of coal measures case study

Kinetic tests
Summary

- Acid Base Accounting data reflects the AMD chemistry data
  - Brunner CM – acid forming
  - Gore CM – mostly non acid forming
  - Paparoa and Morley CM – non acid forming

- This also matches geological observations.
  - Brunner CM are deposited close to the sea, and have transgressive marine sediments overlying.
  - Other rock types are further removed from marine environment, and do not have overlying marine sediments.

- There are trends in Brunner CM ABA data with grain size at a regional scale.
  - More acid forming as grain size decreases
  - At the deposit scale these trends are not always present

- Kinetic testing indicates variable rates of reaction
  - Backed up with recent petrographic studies

Geochemistry of coal measures

Kinetic testing

Weisner & Weber NZJGG 2010
Downstream geochemistry

- Example
  - Island Block and Fanny Creek
    - Brunner Coal Measures
    - Open cast
  - AMD formed
    - Concentration of Al > Fe
    - Most elevated trace element concentrations are Zn and Ni

Acidity in Fanny Creek

[Graph showing calculated acidity load vs flow rate and calculated acidity and pH vs flow rate]
**Summary**

- Acid Base Accounting data reflects the AMD chemistry data
  - Brunner CM – acid forming
  - Gore LM – mostly non acid forming
  - Paparoa and Morley CM – non acid forming
- Reaction rates are variable
- In mine drainage catchments the flux of acid and metals does not dilute with rainfall events

**Case study**
Case Study

• Consent process for a new mine
• Can we predict what the ecological impact would be for a new mine?
• Two stage process
  – What will the water quality be at the compliance point?
  – What is the impact of that water quality on the aquatic ecosystem?
• If there is an unacceptable impact, can we identify a management / remediation strategy that is appropriate?
• Framework document provides assistance with the steps required to get information required for resource consent.

Regional Geology and Analogy

• Regional Geology – includes PAF rocks
• Analogy
Acid Base Accounting

- How many samples?
  - Characterise representative rock types
  - Identify zones or horizons that might have special ABA characteristics

- Framework gives guidance on sample densities
  - Try to capture geological complexity

- What Analyses?
  - MPA, ANC, NAG, paste pH

- Framework recommends that all types of ABA analyses should be conducted at consent stage
  - Streamlined testing procedures should be left if ABA chemistry is well understood at site.

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Mine Drainage Chemistry

- Two approaches
  - Could take the results of the acid base accounting data and apply an analogy with a worst case scenario
  - Or could complete kinetic testing on the rocks to determine the likely mine drainage chemistry

- Assume kinetic testing has been completed with the following results
  - pH 3.2
  - Fe 17 mg/L
  - Al 32 mg/L
  - Acidity 249 kg(HSO₄)/t
  - TSS 1000 mg/L
Reactive transport modelling

- Produces a chemical composition at a specified point downstream
  - Involves geochemical modelling and produces a range of values
  - Should be completed by an experienced geochemist

- Assume reactive transport modelling has been completed with the following results
  - pH 3.4
  - Fe 12 mg/L
  - Al 17 mg/L

- Both kinetic testing and reactive transport modelling can be designed to test any component of the mine drainage and downstream systems
Gold mines and environmental issues

Dave Craw

Mine Drainage Framework

South Island gold deposits

SCHIST HOSTED GOLD VEIN SYSTEMS

Trace Metals: As, Sb pH: c.7

Greenland Group greywacke/schist, Westland

Arsenic, ppm

Gold, ppm
Arsenopyrite (FeAsS) and scorodite (FeAsO$_4$) coating

Calcite (CaCO$_3$)

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Arsenic is extremely soluble at the high pH of gold mines

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Mine excavation:
ore contains As minerals
As dissolves in runoff

Waste rock:
little or no As
runoff has minor As

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Scorodite precipitation (lab experiments)

South Island mine waters

Maximum dissolved arsenic in mine discharge waters

Gold mines

---

As, mg/l
pH

0 1 2 3 4 5 6 7 8 9 10

As, mg/l
0.001 0.01 0.1 1 10 100 1000 10000

0.001 0.01 0.1 1 10 100 1000 10000

0 1 2 3 4 5 6 7 8 9 10

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Drinking water

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Gold mines

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As, mg/l
pH
Processing plant: slurry contains As minerals; As dissolves

Tailings dam: may contain As minerals; water has dissolved As

Processing plant: waste waters with As; As removed before discharge

Minor acidification is an advantage for arsenic suppression

Maximum dissolved arsenic in mine discharge waters
Scorodite precipitation (lab experiments)
South Island mine waters

No addition of lime in site management
Antimony
- Sb^{3+}, Sb^{5+}
- Forms oxyanions
- Widely used historically
- No nutritional use in humans
- Highly toxic to humans (mimics P)

Arsenic
- As^{3+}, As^{5+}
- Forms oxyanions
- Widely used historically
- No nutritional use in humans
- Highly toxic to humans (mimics P)

Macraes “hard rock” gold mine
Production: 300 000 ounces Au/year
Ore: gold = 1.5 grams/tonne
Arsenic ~3000 grams/tonne

Arsenopyrite FeAsS

Truckload: 8 ounces gold + half tonne of arsenic
Gold is encapsulated in pyrite and arsenopyrite; these sulfides are separated by fine crushing and flotation.

PIXE image of arsenopyrite with 2000 ppm Sb, Macraes Mine. Sb is not present as a separate mineral.

Pressure-oxidation autoclave
Concentrate slurry is roasted in oxygen atmosphere at 225°C

Results in acid solution (pH =1) pH raised to 10.5 for cyanidation
Mobilises As and Sb in solution
Large tailings dam, Macraes: contains As-bearing waste. Seeping water returned to mine; no As discharge.

Iron oxide/arsenic precipitate

999,998 grams/tonne of mined rock become tailings

Bulk distribution constants for arsenic and antimony in Reefton iron oxyhydroxide/water

\[ K_d = \frac{\text{Metalloid in solid}}{\text{Metalloid in water}} \]

Craw, Wilson & Ashley 2004

Antimony adsorption/desorption on iron oxyhydroxide

McComb, Craw & McQuillan 2007
Mitigation of trace metal risks for sustainable mining

Mine activity: excavations, tailings

- No oxidation processing at mine
- Oxidation processing at mine

- Maintain water saturation, limit water throughput
- Limit water incursion

- No Fe minerals
- Fe minerals oxidize in air to form Fe oxide

- Adsorption of As, Sb to Fe oxide precipitates

- Discharge water meets consent criteria

Natural revegetation of extremely arsenic-rich mine wastes

Phytoremediation can cover high-arsenic residues and isolate them from the human environment

Plants and many animals are remarkably tolerant of arsenic (unlike humans)
Water from historic underground mine, intersected in drillhole pH = 7, HFO precipitate

Elevated dissolved As (up to 25 mg/L)

Coal Adit entrance

Plant colonisation is progressively covering the HFO apron

Moss is initial coloniser

Ferns, then other plants follow moss

Moss provides a substrate for establishment of other plants

Substrate As: 10-20 wt%
Fern: As 353, 374 mg/kg
Moss: As 1720, 1770 mg/kg

Abundant invertebrates, limited diversity

No invertebrates

Substrate As: 11.6, 12.2 wt%

Griselinia littoralis shoots/leaves
As: 20 mg/kg

NZ native shrubs

Partial burial of plants with later precipitates:
shrubs apparently thrive

Fuchsia excorticata shoots/leaves
As: 30 mg/kg

Substrate As: 10-20 wt%

Prohibition mine processing plant:
Pyrite, arsenopyrite roasted to release Au for cyanidation.

Condense arsenolite, As$_2$O$_3$ as by-product
Oxidation causes acidification:

\[ \text{As}_2\text{O}_3 + 3\text{H}_2\text{O} + \text{O}_2 = 2\text{H}_2\text{AsO}_4^- + 2\text{H}^+ \]

Arsenolite
\[ \text{As}^3\text{O}_3 \]

\( \text{pH} \) down to 3

Dissolved \( \text{H}_2\text{AsO}_4^- \) runoff forms \( \text{Fe}^3\text{AsV}_2\text{O}_4 \cdot 2\text{H}_2\text{O} \) cement (scorodite)

Wetland below processing plant: receiving water for As-rich runoff
Natural plant colonisation

Wetland

Moss, \( \text{Pohlia wahlenbergii} \)
Secondary electron images with As X-ray emission

Moss As:
0.8-3.1 wt%

Water As:
50-77 mg/L

Substrate As:
3-16 wt%
**Fuchsia excorticata** shoots/leaves

As: 30 mg/kg
Sb: 0.05 mg/kg

Iron oxyhydroxide

As: 10-20 wt%
Sb: 100-1000 mg/kg

Electron backscatter images: pale zones = As-rich

**K₃Fe₆[As₅O₁₄][OH]₆·6H₂O (pharmacosiderite)**

Hewlett, Craw, & Black 2005
Craw, Rufaut, Haffert, & Paterson 2007

**As/Sb ratio of plants reflects As/Sb ratio of substrates**

As, mg/kg

**Phytoremediation**

- Revegetation of As-rich mine wastes can isolate the As from the biosphere
- Revegetation of extreme As (>10 wt%) is possible with grasses, mosses, ferns and shrubs
- Shrubs and grasses are most effective, if pH >5 (low As uptake)
- Mosses are effective for initial colonisation (high As uptake)
North Island gold

- Epithermal (hot spring) systems
- Abundant pyrite
- Abundant base metals: Cu, Pb, Zn, Cd
- Little carbonate
- Acid drainage from natural and man-made outcrops and deposits

Volcanic-hydrothermal zones

Northland
Coromandel Peninsula
Waihi
Te Aroha
Taupo Volcanic Zone

Trace Metals:
As, Hg
pH: c.1-6

Trace Metals:
As, Cd, Cu, Pb, Sb, Zn (+Al, Fe, Mn)
pH: 1-7

Martha mine, Waihi: 18 million tonnes of ore with 3 g/tonne Au
Acid neutralisation capacity (ANC) wt% CaCO₃ (equivalent)

Maximum potential acidity (MPA), wt% CaCO₃ (equivalent)

Acid-base accounting
Net neutralising rocks

Divalent cations are soluble at low pH, opposite to arsenic, antimony (oxyanions)

Summary of principal environmental issues arising from two types of gold mining in New Zealand
Environmental effects of alluvial gold mines

- Most alluvial gold mines have no AMD
- Some Southland sedimentary rocks have pyrite or marcasite (both Fe\(\text{S}_2\))
- Sulphides occur with woody material below the water table
- Sulphides were added to rock by groundwater AFTER rock deposition,
Glenore Au mine, Milton, South Otago

Pyrite in dark layer, associated with wood

Belle-Brook, Southland Au deposit

1 cm

Marcasite (FeS$_2$) replaces wood

Arsenopyrite is stable under reducing conditions e.g., deep groundwater, & river beds

Scorodite
FeAsO$_4$.2H$_2$O

Fe(OH)$_3$ + As(V) (aq)

Fe(OH)$_3$ + As(III)(aq)

Fe$^{2+}$ + As(III)(aq)

Iron$^{2+}$ + HAsO$_4$$^-$ + 11H$^+$ + 11e$^-$ + SO$_4$$^{2-}$

Arsenopyrite

FeAsS

AsS

SAs = SFe = 10$^{-5}$ mole/litre

SS = 10$^{-4}$ mole/litre

Fe$^{2+}$ + As(III)(aq)
Arsenopyrite transported long distances in rivers

Alluvial mines and AMD

• Most alluvial gold mines have no AMD

• Local sulphides can lead to AMD, as for coal, with the same predictions for water quality

• Sulphide distribution is difficult to predict: different from marginal marine coal

• Minor arsenic from detrital arsenopyrite and from solid solution in pyrite or marcasite

Case study
Proceed (with ongoing monitoring)

What is the potential for a detrimental ecological impact?

What is the level of potential impact?

Decision-making step

Is this an ‘acceptable’ level of impact for this system?

No

How do we reduce impact to an ‘acceptable’ level?

Operational Management

Treatment during operation

Yes

Is this an ‘acceptable’ level of impact for this system?

Summary of what information is available at this point

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<td>Stream chem</td>
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<td>Fe³⁺/Fe²⁺</td>
<td>9.1</td>
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</table>
1. What is the ecology of a natural stream?
2. How do we measure ecological impacts?
3. Mechanisms of mine impacts
4. Acid & metal toxicity (coal, hard rock gold)
5. What effects might alluvial gold mining have?
6. Case study application
When we started

- Algae (periphyton)
- Dissolved organic matter (DOM)
- Bacteria & fungi
- Stream invertebrates
- Moss & Larger plants
- Fish & crayfish

Approach

1. Literature reviews
2. Field surveys
3. Toxicity trials

Toxicity trials

- Acute (lethal) and chronic (sublethal)

LC50 = lethal concentration
Amount of substance given at once on a short term which causes the death of 50% of a group of test animals.
Mine outputs which effect stream communities

- pH
- Metals e.g. Fe, Al, Ni, Zn, Al precipitates

Confounding factors in measuring stream health

- Algae (periphyton)
- Bacteria & fungi
- Dissolved organic matter (DOM)
- Stream invertebrates
- Moss & Larger plants
- Fish & crayfish

?
What happens to leaf decomposition in AMD streams?

Barnden (2005)
Barnden & Harding (2005)

How are algal communities affected by AMD?

Bray (2007)
Bray et al (2008)
How are invertebrate communities affected by pH?

Niyogi & Harding (2007)
Kitto (2009)
Acid Mine Drainage Index
Study Sites

- 91 sites, invertebrates
- **AMD variables**
  - pH,
  - Metals (CCU),
  - Conductivity,
- **Conditioning variables**
  - Location,
  - Disturbance,
  - Stream size,
  - Substrate

---

**AMD Impact Gradient**

- Neutral pH
- Low metals
- High metals
- Acid

**Weighted Averaging (WA)**

- Indicator score
  - 10 9 8 7 6 5 4 3 2 1 0

---
**Acid Mine Drainage Index**

AMDI Site Score = \( \left( \frac{\sum b_i}{c} \right) \times \log_{10} c \) \times 10

Where \( b \) is a taxon indicator value and \( c \) is the total number of scoring taxa found in the samples. AMDI scores range from 0-100, with a higher score indicating a lesser degree of AMD impact.

**Impact groupings**

Likely water quality

<table>
<thead>
<tr>
<th>AMDI range</th>
<th>Impacted</th>
<th>Moderately impacted</th>
<th>Unimpacted</th>
</tr>
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<tr>
<td>&lt; 20</td>
<td>Impacted</td>
<td>20 to 40</td>
<td>Unimpacted</td>
</tr>
<tr>
<td>&gt; 40</td>
<td>Impacted</td>
<td></td>
<td>Unimpacted</td>
</tr>
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</table>

**MCI**

- Severely impacted
- Impacted
- Unimpacted

- Excellent
- Good
- Fair
- Poor
Mayflies sourced from different pH

Source pH = 7.4

Survival (%)

Time (hrs)

Source pH = 7.0

Survival (%)

Time (hrs)

Source pH = 7.0

Survival (%)

Time (hrs)

Source pH = 6.5

Survival (%)

Time (hrs)

Source pH = 5.9

Survival (%)

Time (hrs)

Source pH = 5.7

Survival (%)

Time (hrs)

Mayfly tolerance to AMD depends on the pH of their home stream.

Effect of pH on other species

Toxicity trials testing Al toxicity - acute

LC₅₀ ~ 100-330 mg/L
Toxicity trials testing Al toxicity - chronic

LC₅₀ 1.46 mg/L

Toxicity trials testing Fe toxicity

LC₅₀ 53 mg/L

Effect of iron precipitate
Hard rock gold mining

Arsenopyrite FeAsS

Truckload: 8 ounces gold + half tonne of arsenic

Toxicity trials testing Arsenic toxicity

Acute (96-hr) LC\textsubscript{50} – 2.5-3.7 mg/L

Chronic (14 day) LC\textsubscript{50} – 0.36 mg/L

Drinking water guideline 0.010 mg/L

Algae (periphyton) → Bacteria & fungi → Stream invertebrates → Fish & crayfish

Dissolved organic matter (DOM) → moss & larger plants
Tolerance of common freshwater fish to pH

- Bluegill bully
- Torowhanu
- Shortjaw kokopu
- Brown trout
- Redfin bully
- Banded kokopu
- Common bully
- Longfin eel
- Koura
- Giant kokopu
- Shortfin eel
- Inanga

Stream pH

Alluvial gold mining

Turbidity

Before mining

During mining
Impact of turbidity

- Algae (periphyton)
- Bacteria & fungi
- Moss & Larger plants
- Fish & crayfish

Impact of turbidity

- Photosynthesis
- Productivity
- Schooling ability
- Gill irritation
- Predator/prey relationship
- Stress
- Feeding efficiency
- Smothering of non-mobile organisms and eggs
- Growth
- Prolonged hatching time

Where to from here?

- Fill gaps (suspended solids)
- Issues in different regions - Waikato/Coromandel
- Invertebrate mining community index...
Case study

Proposed operations

- What is the potential for a detrimental ecological impact?
- What is the level of potential impact?

Decision-making step

- Is this an ‘acceptable’ level of impact for this system?
  
- No
  - How do we reduce impact to an ‘acceptable’ level?
  - Operational Management
  - Treatment during operation

Yes
- Proceed (with ongoing monitoring)

Case study

- Stage 1&2 predicted chemistry of receiving water
  - pH 3.4, Al 17 mg/L, Fe 12 mg/L
- Stage 3 predicted chemistry of receiving water
  - pH 3.6, Al 7 mg/L, Fe 9 mg/L
Outcome 1 & 2

Algae (periphyton)

Bacteria & fungi

Dissolved organic matter (DOM)

Stream invertebrates

Fish & crayfish

Moss & Larger plants

pH 7

Dissolved metal

Decision-making

• ‘Acceptable’ level of impact determined through consultation processes
  – applicant and regulatory agencies
  – wider consultation

• For case study purpose: impacts are unacceptable – management or treatment of mine discharge is required
Remediation chemistry

Active treatment

Passive treatment

Case study

Low pH
High metal load

Neutral pH
Clean water

Treatment = add neutralising agent to raise pH
Due to low solubility at high pH, metals precipitate
60 L/s
pH 3.1
Fe 11 mg/L
Al 14 mg/L

1 L/s
pH 3.0
Fe 60 mg/L
Al 40 mg/L

20 L/s
pH 6.0
Fe 25 mg/L
Mn 18 mg/L
DO < 1 mg/L
• Often low pH

• Usually rich in acidic metals
  – Al and Fe

• Often elevated trace elements
  – As, Ni, Zn, Cu, Cd, Pb, Mn

• Sometimes neutral pH with trace elements
  – Mn, As, Sb, (Fe)
Treatment goals

Neutralisation
Removal of acidic metals
Removal of trace elements

Neutralisation
• Na or Ca based chemicals (carbonate or oxide/hydroxide) or ammonia
  • NaCO₃, NaOH, CaCO₃, CaO, Ca(OH)₂
  • NH₃ or NH₄OH
• Commonly CaCO₃ or Ca(OH)₂
  • CaCO₃ + 2H⁺ → H₂CO₃ + Ca²⁺ → CO₂(g) + H₂O + Ca²⁺
  • Ca(OH)₂ + 2H⁺ → Ca²⁺ + 2H₂O
• Not just H⁺ but must neutralise acidic metals too

Acidity produced through metal precipitation
• Fe²⁺ + ½O₂ + 5/2H₂O → Fe(OH)₃ + 2H⁺
• Fe³⁺ + 3H₂O → Fe(OH)₃ + 3H⁺
• Mn²⁺ + ½O₂ + H₂O → MnO₂ + 2H⁺
• Al³⁺ + 3H₂O → Al(OH)₃ + 3H⁺
Removal of acidic metals

**Oxidation = hydroxides**

- Elevated Fe(II) common
  - Highly soluble
  - Oxidises to Fe(III) – slowish process
  - Fe(III) precipitates Fe(OH)₃ rapid process

- Fe²⁺ + H⁺ + ½O₂ → Fe³⁺ + ½H₂O
- Fe³⁺ + 3H₂O → Fe(OH)₃ + 3H⁺

Removal of acidic metals

**Reduction = sulphides**

- Iron reducing bacteria, sulphate-reducing bacteria
  - Fe(III) reduced to Fe(II)
  - Sulphate reduced to metal sulphides
  - Organic material as energy source

- 2CH₂O + SO₄²⁻ → H₂S + 2HCO₃⁻
- M²⁺ + H₂S → MS + 2H⁺
- 2H⁺ + 2HCO₃⁻ → CO₂ (g) + 2H₂O

Pathway to pyrite
Removal of trace elements

- Oxidation - Fe(III) precipitates
  - Large surface area adsorbs trace elements
  - Effectiveness variable
    - Depends on ratio of precipitate to trace elements
    - Depends on pH
    - Depends on competition for sites between elements

Reduction - Fe\textsubscript{3+}, FeS\textsubscript{2}

- Sulphides are often impure minerals – contain several weight % non-essential elements
- Many trace elements form stable sulphides under reducing conditions.

Treatment methods

- Active treatment
  - Engineered water treatment plant
  - Constant addition of reagents
  - Reliable and effective but costly
  - Generally more common at operational mines

- Passive treatment
  - No continuous dosing with chemicals
  - Takes advantage of naturally occurring chemical and biological processes
  - Less costly in the long term
  - Generally more common at abandoned mines

Active treatment
Dosing with alkali

Calcium hydroxide

Ca(OH)\textsubscript{2} + 2H\textsuperscript{+} → Ca\textsuperscript{2+} + 2H\textsubscript{2}O

Calcium hydroxide

Powdered limestone

Ca(OH)\textsubscript{2} + CO\textsubscript{2} + H\textsubscript{2}O → Ca\textsubscript{2}(CO\textsubscript{3})\textsubscript{2} + 6H\textsuperscript{+} → Ca\textsuperscript{2+} + 2H\textsubscript{2}O
Sodium hydroxide

Sodium bicarbonate

\( \text{Na}_2\text{CO}_3 + 2\text{H}^+ \rightarrow \text{CO}_2\text{(g)} + \text{H}_2\text{O} + 2\text{Na}^{2+} \)

Ammonia gas

\( 2\text{NH}_3 + \text{Fe}^{2+} + \text{SO}_4^{2-} + 2\text{H}_2\text{O} = (\text{NH}_4)^+\text{SO}_4 + \text{Fe}^{2+}\text{OH}_2 \)

Calcium oxide
Selecting active treatment

- Chemistry and flow rate
- Cost of chemical
- Neutralising efficiency
- Max pH attainable
- Dispensing method
- Mixing requirements

- Limitations
- Risk of failure
- Health and safety issues
- Available land area
- Sludge settling rates
- Sludge density

Passive treatment

Magic rocks of passive treatment
Remediation strategies

Oxidising
Add alkalinity, add DO
- Raise pH
- Oxidation of all Fe$^{2+}$
- Precipitate hydroxides - Fe(OH)$_3$, Al(OH)$_3$

Reducing
Strip DO, add alkalinity
- Reduction of all Fe$^{3+}$
- Reduction of sulphate
- Precipitate sulphides - FeS$_2$, FeS
- Raise pH

Open limestone channel
Steel slag leaching bed
(calcium oxide)

Limestone sand dosing
Diversion well

Anoxic limestone drain

Fe^{2+} and Mn^{2+} stable at high pH
\[
\text{CaCO}_3 + 2\text{H}^+ \rightarrow \text{CO}_2(g) + \text{H}_2\text{O} + \text{Ca}^{2+}
\]
\[
\text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^-
\]
\[
\text{HCO}_3^- + \text{H}^+ \rightarrow \text{H}_2\text{O} + \text{CO}_2
\]

Increase in DO
\[
\text{Fe}^{2+} + \text{H}_2\text{O}_2 \rightarrow \text{Fe}^{3+} + \frac{1}{2}\text{H}_2\text{O}
\]
\[
\text{Fe}^{3+} + 3\text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 3\text{H}^+
\]
Reducing and alkalinity producing system

\[ \text{Fe}^{3+} + \text{SO}_{4}^{2-} \rightarrow \text{Fe}^{2+} + \text{H}_{2} \text{S} \]

Increase pH
Increase alkalinity

remove DO

M^2+ → MS
Bioreactor

remove DO

Fe^{3+} \rightarrow Fe^{2+}

SO_4^{2-} \rightarrow H_2S

Mn^{2+} \rightarrow MS
Wetlands
anaerobic, aerobic

Wetland benefits

- Solids removal
- Treatment polishing/buffer
- Ecological values
- Mitigation credits
- Educational values

Use of ponds in passive systems

- Promote oxidation
  - Fe oxidation for high Fe²⁺ waters
  - BOD, colour, smell for water from organic substrates
- Promote solids formation
  - Mixture of alkaline – acid waters
- Promote settling
  - Fe solids formed with Fe²⁺ oxidation
  - Lessen TSS before flowing into passive systems

25/08/2011
Selecting passive treatment

- Chemistry
  - Fe concentration
  - Al concentration
  - Fe$^{2+}$/Fe$^{3+}$ ratio
  - DO

- Topography

- Available land area

System design

e.g.: ALD

- Determine design flow and average flow
- Determine limestone purity
- Determine tonnes limestone needed
  - Need 12-15 hours contact time for maximum alkalinity
  - Need additional for dissolution over 25 yr
  - Usually about 6 tonnes/Lpm
- Complete conceptual design
  - Incorporate land area, topography
  - Must completely exclude oxygen within system
  - Limestone size = 6-15 cm diameter
  - Need cascade on exit to increase DO
  - Design pond for oxidation and capture of precipitates

Current research

- Armouring of limestone
  - Is it just Fe, or gypsum and Al too?
  - How prevent or accommodate?
  - What is the Fe threshold level?
  - Does gradient to OLC really help?

- Reduction of permeability and formation of preferential pathways
  - Larger limestone rocks?
  - More frequent flushing?
  - More rapid flushing?
  - Horizontal/vertical flow hybrids?

- Sludge
  - Does flushing really remove precipitates from systems?
  - How stable is sludge?
  - What can we do with it?
Case study

**Proposed operations**

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- What is the level of potential impact?

**Decision-making step**

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</table>

| Years | 10 | 10 |
| Flow (L/s) | 100 | 10 |
| pH | 3.2 | 3.2 |
| Fe (mg/L) | 15 | 10 |
| Al (mg/L) | 32 | 9 |
| Acidity (mg/L) | 249 | 212 |
| TSS (mg/L) | 1000 | 100 |
| Fe<sup>3+</sup>/Fe<sup>2+</sup> | 9.1 | |

**Potential ecological impact = Outcome 1**

**Acidity > 800 mg/L**

**Acid Load > 150 kg/day**

(acidity (mg/L) x flow rate (L/s) x 0.0864)

**Consider Passive Treatment**

See Passive Treatment Flow Chart

**Operational Mine**

See Text

**Consider Active Treatment**

See Active Treatment Flow Chart

### Stages 1 & 2

- **Year**: 10
- **Flow (L/s)**: 100
- **pH**: 3.2
- **Fe (mg/L)**: 15
- **Al (mg/L)**: 32
- **Acidity (mg/L)**: 249
- **TSS (mg/L)**: 1000
Overburden management

- Water diversion
- Segregation PAF/NAF
- Encapsulation
- Layering
- Blending
- Cover design
Stage 3

Mine drains - chem
Stream chem

Potential ecological impact - Outcome 1

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<th>Flow (L/s)</th>
<th>pH</th>
<th>Fe (mg/L)</th>
<th>Al (mg/L)</th>
<th>Acidity (mg/L)</th>
<th>TSS (mg/L)</th>
<th>DO (%</th>
<th>Fe³⁺/Fe²⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2</td>
<td>2.8</td>
<td>30</td>
<td>10</td>
<td>212</td>
<td>200</td>
<td>90</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Acidity > 800 mg/L
Acid Load > 150 kg/day
(acidity (mg/L) x flow rate (L/s) x 0.0864)
Consider Passive Treatment
See Passive Treatment Flow Chart

Consider Active Treatment
See Active Treatment Flow Chart

Operational Mine

Passive Treatment Flow Chart
Summary

- **Treatment Chemistry**
  - pH, acidic metals and trace elements
  - Neutralisation, oxidation, reduction, adsorption

- **Active Treatment**
  - Engineered water treatment plant
  - Constant addition of reagents
  - Reliable and effective but costly
  - Requires operation, monitoring and maintenance

- **Passive Treatment**
  - No continuous dosing with chemicals
  - Takes advantage of naturally occurring chemical and biological processes
  - Less costly in the long term
  - Can fail if not carefully selected and designed
Regulatory background and a framework for predicting and managing water quality impacts of mining on streams

Jo Cavanagh

Regulatory background

  - Minerals Permit
  - Permission of land owner for access
    - Public conservation land - permission is required from the Minister of Conservation
- Resource Management Act 1991
  - Resource consents
  - Regional plans
  - Schedule 3 Water quality classes
Generalised Resource Consent Process

Application submitted to RC
Application assessed for sufficient information
[Decision made on notification]
Notified, submissions received
Decision made on pre-Hearing meeting, Hearing
Decision on proposed activity made and issued
Appealed?
Consent issued if granted

Information required includes:
Assessment of environmental effects (AEE)
Additional information required by council plans or regulations

Developing a framework

- Recognition of improvement in existing regulatory process for mining applications
  - Existing widely-used water quality guidelines (ANZECC) not necessarily applicable
- Improvement in public perception of mining and decision-making around mining applications

How did we develop the framework?

- Fundamental research
- Provided drafts for comment to DOC, WCRC, SENZ, Pike River, Consultants
- Evaluation of framework alongside current applications for mining (DOC, WCRC)
- Peer review
Our aims

• Provide science information to end-users in a useful manner
• Facilitate consistency in regulatory decision-making, including information required
• Assist:
  – meeting regulatory requirements
  • Access arrangements (AEE), DOC
  • Resource consents (AEE, discharge consents), Regional Plans
  – internal decision-making for mining companies

Potential application

What the framework does

• Focus is water quality issues downstream of mine
  – primarily pH, and metals
  – turbidity
• Provides a guide for non-experts to the main water quality issues
• Provides some robust new science, fills some gaps
What it doesn’t do…

- Address other water quality or environmental issues
  - water temperature
  - stream diversions
  - water quantity
  - subsidence issues.
  - noise, traffic, visual, dust
- Nor does it cover all situations

What is the framework?

- A flow chart outlining a decision-making process
- Supporting information:
  - Data requirements
  - Guidance for on-going monitoring
  - Databases
- Format
  - Online, downloadable PDF

![Proposed operations flow chart](chart.png)

Decision-making step: Is this an 'acceptable' level of impact for this system?

- Yes
  - Proceed (with ongoing monitoring)
- No
  - How do we reduce impact to an 'acceptable' level?

  Operational Management
  Treatment during operation
What is the potential for a detrimental ecological impact?

What is the level of potential impact?

Proposed operations

Water chemistry

Biological information

Proposed operations

Water chemistry

Biological information

Decision-making step + Is this an ‘acceptable’ level of impact for this system?

‘Framework does not specify what is “acceptable”, rather it allows for

• Site-specific considerations

• Other social and economic considerations

‘Acceptable’ level of impact determined through consultation processes

– applicant and regulatory agencies

– wider consultation
Proposed operations

What is the potential for a detrimental ecological impact?
What is the level of potential impact?

Decision-making step
Is this an ‘acceptable’ level of impact for this system?

No
Operational Management

How do we reduce impact to an ‘acceptable’ level?

Yes
Proceed (with ongoing monitoring)

Treatment during operation

Step by step guide

• Step 1. Collate background information (Regional geology, data on receiving system)
• Step 2. Collect rock samples for geochemical testing
• Step 3. Geochemical testing to determine acid-forming status of rock samples
• Step 4. Predict of mine drainage chemistry from geochemical tests
• Step 5. Predict stream water chemistry at a downstream point of interest

Step by step guide

• Step 6. Determine the ecological impact on the receiving system
• Step 7. Consider whether impacts are acceptable
  — If unacceptable go to step 7a
  — If acceptable go to step 8
• Step 7a. Decide on management and treatment strategies to create acceptable stream water chemistry and thus achieve an acceptable level of impact
• Step 8. Design ongoing monitoring programs
Framework document

- Main text
  - 9 chapters
  - Checklists at end of each chapter
  - Worked example
- Appendices with detailed technical information

Available at:
- Coal – PAF (Chapter 4)
- Coal – NAF (Chapter 5)
- Gold – hard rock (Chapter 6)
- Gold – alluvial (Chapter 7)

Historical and baseline data (Chapter 2)
- Geological
- Biological

Determining downstream water quality (Chapter 3)
- Commodity
- Geology
- Background water quality

Common information

Mine types
- Coal – PAF (Chapter 4)
- Coal – NAF (Chapter 5)
- Gold – hard rock (Chapter 6)
- Gold – alluvial (Chapter 7)

Decision-making and Monitoring (Chapter 8)
- Rock
- Treatment
- Water quality
- Biological

References and additional reading (Chapters 10 and 11)

Worked example

References
2 Predicting potential ecological impacts on streams
2.1 Introduction
2.2 Historical data
2.3 Baseline information
   2.3.1 Site hydrogeology
   2.3.2 Baseline chemical water quality
   2.3.3 Baseline biological monitoring
   2.4 Checklist

3 Mine drainage and downstream water chemistry
   3.1 Introduction
   3.1.1 Commodity and region
   3.2 Analysis of rocks from the proposed mine site
   3.2.1 Important minerals and field observations
   3.2.2 Sampling strategies for geochemical characterisation of rocks
   3.2.3 Acid-base accounting (ABA)
   3.2.4 Geochemical testing to assess the trace element content of rocks
   3.2.5 Assessing the reactivity of rocks - kinetic tests
   3.3 Prediction of water quality downstream of a mine
   3.3.1 Site hydrogeology
   3.4 Checklist

Process for determining downstream water quality

- Characterise drainage pattern and size
- Characterise rocks that will be disturbed by mining
- Collect flow data under typical stream flow conditions
- Collect geochemical data under typical stream flow conditions
- Reactive transport modelling
- Predict mine drainage chemistry using frameworks
- Predict mine drainage volume from site hydrogeology and mine plan
- Prediction of water quality downstream of mine
Mine type chapters

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Worked example

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Appendices

- Regulatory background
- Suspended solids
- Geochemistry
- Biological impacts and monitoring
- Waste rock management
- Treatment
- Extreme events

Future plan

- Update framework based on recent research (arsenic, antimony)
- 1 year further funding – focus is turbidity, extension in Waikato/Coromandel
- Updating of framework to integrate research results (and any subsequent end-user feedback)
Wrap-up

Dave Trumm

Research team.....

Geology and Geochemistry

Freshwater biology & ecotoxicology

Management and treatment

Policy and Regulation

Geology / Geochemistry

- Mine drainage chemistry
  - Correlation between rock types/depositional environment and acidity
  - Mine type influences the mine drainage chemistry
  - Gold mines can contain significant As and Sb drainage

- Rock geochemistry
  - Interpretation of Acid Base Accounting data
  - Acid Base Accounting data reflects the AMD chemistry data
  - Kinetic testing indicates variable rates of reaction

- Implications for downstream
  - Flux of acid and metals does not dilute with rainfall events
Biological impacts

• Greater understanding of effects of mine drainage on New Zealand aquatic ecosystems
  – Greater understanding of water chemistry required for healthy, functioning stream system

• Focus has been pH, Fe, Al – acid mine drainage, As-gold mining

• Still knowledge gaps
  – TSS
  – Different metals/circumneutral stream

• Much improved methods for testing and monitoring (e.g. BACI design). This more robust and dependable

Remediation

• Remediation chemistry
  – Wide variability in chemistry requires different approaches
  – A suite of options for neutralisation
  – Two major strategies for removing acidic metals and trace elements

• Active treatment
  – Three step process: dosing with alkali, oxidation, sedimentation
  – Multiple variables affect treatment selection

• Passive treatment
  – Drainage chemistry can dictate remediation strategy
  – Available land area significant variable in treatment selection
  – Novel treatment solutions for As and Sb
Framework

- Science from the programme drawn into the Framework
- Designed to:
  - Assist information collection and interpretation during mine consenting
  - Bridge the gap between mining companies, regulators, DoC, and other stakeholders
- New release scheduled for October 2011, incorporating new research over the last year (Sb, As) and review comments

Forthcoming year

- Research on management and effects of suspended solids
- Extension of framework into Coromandel/Waikato region

Thank you for your participation.
Discussion points

• Are there additional or specific areas you think science research is lacking and would be useful?
  – eg: rehabilitation, effects on groundwater...

• Is the Framework useful in the work you do?

• Are there gaps in the Framework?
  – eg: closure planning

• Is guidance on ongoing monitoring useful?
  – How much detail is needed
Publications arising from the research programme

Geochemistry


Pope J 2010. Current New Zealand mine drainage research. New Zealand Journal of Geology and Geophysics, 0: 0, 89. [Introduction]


Biology


**Remediation**


Framework


