Understanding Mineralogical Composition, Weathering, and Alteration, to Manage ML/ARD in a Base-Metal Tailings Storage Facility

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Outline:

Background
Project Objectives
Site Overview
Approach and Methodology
Results
Conclusions
Lessons Learned
Weathering is the breakdown of rocks and minerals, by physical, chemical or biological processes.

Chemical weathering = mineralogical alteration.
- Dissolution / Desorption
- Oxidation and Neutralization

Sulphide dissolution and oxidation + carbonate and silicate dissolution and neutralization $\rightarrow$ mineralogical changes over time in TSFs.

\[
\text{CaCO}_3(s) + H^+(aq) \rightarrow \text{Ca}^{2+}(aq) + \text{HCO}_3^-(aq)
\]
Demonstrate that mineralogical identification is essential to geochemical assessments.

Changes to primary and secondary minerals in a TSF → Evolving porewater and tailings seepage.

Understanding mineralogy and reactivity to manage ML/ARD in TSFs is critical in maintaining regulatory compliance and meeting operational and closure objectives.
• Geochemical changes were evident at a flooded base-metal TSF:
  • TSF >1000 km²; tailings deposition >90 yrs to present in > 10 individual areas (A-J).
  • Impacted surface and pore water quality:
    • Seepage from older areas well exceeded regulatory guidelines prior to treatment.
    • Seepage from younger areas was getting worse.
  • Secondary minerals were observed as a product of changing geochemical conditions.
  • Geochemical assessments predicted PAG tailings. No WQ predictions were made.
• Evolution of tailings mineralogy as it relates to changing porewater and seepage water quality in the ageing TSF was largely unknown.
**Drilling Program**

- Sonic drilling methods—intact core!
  - 48 boreholes/10 areas
  - Max depth 80 m (avg. 40 m)
  - TSF stratigraphy (~2 km) described at 30 cm intervals;
    - Unified Soil Classification System (USCS)
    - Munsell colour
    - Notable physical characteristics
  - Field measurements:
    - Paste pH, ORP, EC and TDS
  - Subsampled intervals (n = 150) for geochemical testing and mineralogical analysis → **Material Characterization**

**TSF Surface and Pore Water Monitoring:**

- 10 disposal areas
  - Paired shallow and deep wells; crest, ± bench, toe; located in section
  - Upstream reservoirs and downstream seeps
  - Extensive parameter list:
    - pH, Eh, EC, TDS, TSS, alkalinity, acidity;
    - Total and dissolved anions/cations, FeII/FeIII.
  - Monthly >3 years → **Water Monitoring**

Surface water: upstream reservoirs (1) and downstream seepage collection ponds (6);
Pore water: monitoring wells (2, 3, 4);
Seepage water: passive dam toe seeps and engineered drains, pipes, and, culverts (5).
Approach and Methodology

- **Mineralogical Composition**
  - Optical microscopy
  - X-Ray Diffraction
  - Scanning Electron Microscope

- **Chemical Composition**

- **Acid Base Accounting**
  - Modified Sobek
  - AP and NP
  - Method used to understand the ARD potential of the bulk material.

- **Net Acid Generation Tests**
  - Aggressive oxidation $\text{H}_2\text{O}_2$
  - Method used to estimate net reactivity.

- **Single Batch Leachate Extractions**
  - Standard shake flask extraction (SFE) (pH 5.5) + Modified SFE (pH 2.2)
  - Method used to measure the short-term metal leaching potential (soluble phases) under sub-neutral and acidic solutions
  - Soluble phases = Secondary surface coatings or sorbed species and soluble primary or secondary minerals

- **Kinetic Tests**
  - ASTM methods
  - Rate of sulphur oxidation under lab controlled settings.
  - Method used to understand ML/ARD.

- **Site Specific Monitoring**

- **Major and trace element analysis**
  - XRF;
  - 4 acid digest and ICP-MS/AES.
  - Method used to understand the chemical composition of the bulk material.
Water quality results depend on location, material age and surrounding physiochemical conditions:

- pH, Eh, temperature, surrounding minerals

Water quality evolves with progression from shallow to deeper porewaters before emerging as seepage:

- Acidic upstream reservoir, less acidic shallow pore water, sub-neutral deep pore water and progressively acidic seepage.
Disposal Area B: Active 1945-1979

Disposal Area J: Active 1985-present
Tailings Material Characteristics

Oxidized Zone
Surface to 4 m in older areas, 1.5 m in younger area
Little to no visible sulfide minerals
Extensive mineral alteration and oxidation

Transition Zone
Intermittent depths
Trace to some visible sulfide minerals
Moderate mineral alteration and oxidation

Unoxidized Zone
10 m below surface in older areas, 3 m below surface in younger areas
Abundant visible sulfide minerals
Some mineral alteration and minor oxidation

TSF Stratigraphy

Area F: Revegetated historic depositional area
Tailings Geochemical Results

- Depth (ft) vs. Paste pH
- Depth (ft) vs. Total Fe (ug/g)
- Depth (ft) vs. Total Ca (ug/g)
- Depth (ft) vs. Total Ni (ug/g)
- Depth (ft) vs. Total S (ug/g)

Disposal Areas: A, B, C, D, E, F, G, H, I, J

Graphs show the distribution of various elements with depth.
Tailings Geochemical Results

1. **Paste pH vs. Depth (ft)**
2. **Total Fe (ug/g) vs. Depth (ft)**
3. **Total S (ug/g) vs. Depth (ft)**
4. **Total Ca (ug/g) vs. Depth (ft)**
5. **Total Ni (ug/g) vs. Depth (ft)**

Each graph displays data for different disposal areas:
- Disposal Area A
- Disposal Area B
- Disposal Area C
- Disposal Area D
- Disposal Area E
- Disposal Area F
- Disposal Area G
- Disposal Area H
- Disposal Area I
- Disposal Area J

The graphs show the distribution of various elements at different depths, with colors representing different disposal areas.
### Initial Tailings Mineralogy:
- Pyrrhotite, pentlandite, chalcopryite, pyrite, ± cobaltite, sphalerite and galena.
- Quartz, feldspar, pyroxenes, amphiboles, micas, ± carbonates and clays.

### Minerals React:
- Pyrrhotite > galena > sphalerite > arsenopyrite > pyrite > chalcopryite > magnetite
- Calcite >> Clays > Framework Silicates >>> Quartz

### Minerals Form:
- Gypsum, Gibbsite ± Ferrihydrite ± Schwertmannite → Goethite and Alunite/Jarosite

### Mineral Group

<table>
<thead>
<tr>
<th>Mineral Group</th>
<th>Disposal Area A: Late Stage ARD</th>
<th>Disposal Area J: Early Stage ARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicates</td>
<td>Feldspar (Ca), Quartz, Pyroxene, Hornblende and Clays</td>
<td>Feldspar (Ca + K + Al), Mica, Quartz, Pyroxene, Hornblende</td>
</tr>
<tr>
<td>Sulphides</td>
<td>Chalcopryite, Chalocite, Pyrite</td>
<td>Pyrrhotite, Marcasite, Chalcopryite, Pyrite</td>
</tr>
<tr>
<td>Sulphates, Oxides, Hydroxides</td>
<td>Gypsum, Jarosite, Goethite</td>
<td>Wuestite, Alunite, Gypsum, Jarosite</td>
</tr>
</tbody>
</table>

Example: Partially oxidized Zone
Summary

Surface Oxidized Tailings
Partially Oxidized Tailings
Less Oxidized Tailings

O$_2$ (atm)
Decreasing Eh
Acidic Pore Water

$\text{Fe}^{3+}$(aq) $\rightleftharpoons$ $\text{Fe}^{2+}$(aq)

Increasing Mobility/Migration

Fe$_2^+$(1ry) $\rightleftharpoons$ Fe$_2^+$(2ry) $\rightleftharpoons$ Fe$_3^+$(2ry) Mins

Increasing pH

Fe$_3^+$(2ry) (Fhy, Goe)
Fe$_2^+$(2ry) (Mel, Cop)

Decreasing Sulphide Oxidation,
Increasing Neutralization Reactions

Migrating Oxidation Front

Hardpan

Fe$_2^+$(aq) $\rightleftharpoons$ Fe$_2^+$(1ry) $\rightleftharpoons$ Fe$_2^+$(2ry) $\rightleftharpoons$ Fe$_3^+$(2ry) Mins

Limited Sulphide Oxidation

Unoxidized Tailings

Blowes et al. 2003
• Sulphide-bearing tailings mineralogically alter through geochemical processes that depend on:
  • Initial tailings mineralogical and chemical composition,
  • Hydrology, and climate;
  • Pore gas content and pore water chemistry
  • Physiochemical conditions
  • Time
• Porewater and seepage concentrations change over time and can eventually exceed regulatory discharge limits.
• Static geochemical testing does not always reflect site specific conditions with time.
• Mineral alteration processes are complex:
  • Leads to changes to surface and pore water leachates
    • Varying pH: from the release and mobilization of acidity balanced by neutralization reactions,
    • Increased concentrations of metal-, metaloid- and anionic-species.
Lessons Learned

• Assessing the hydrogeochemistry and predicting the short- and long-term drainage chemistry of a mine site:
  • Requires a great deal of site specific information,
  • Extensive material sampling plans,
  • Analytical methods, testing and calculations.

• Mineralogical information helps to understand lab results and translate them to ML/ARD reactions on site.

• Results from ageing facilities helps to expand the knowledge of ML/ARD under site specific conditions and over progressively longer periods of time.
  • Better management of environmental impacts.
Thank You!

Questions?