Applications of geometallurgy for waste characterisation across the mining value chain

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What is ‘geometallurgy’?

Purpose: Increase profits
Keeney (2008): Aimed to propagate measured processing attributes (i.e., hardness, grindability) down in the matrix to Level 2 and Level 1.

Defined linkages are essential.
Defined linkages are essential

Geometallurgy Matrix concept

For mine waste characterisation a geometallurgical matrix approach could be readily adopted to de-risk projects and improve long-term financial outcomes.

Representative sampling to capture heterogeneity is a key issue- this helps overcome it.

Requires the embedding of geoenvironmental proxy tests at the earliest LOM stages (i.e., exploration/prefeasibility).
The (enviro)geometallurgy tool kit

- Handheld tools
- Hyperspectral mineralogy
- ‘Next-gen’ technologies
- Simple chemical tests
- Automated mineralogy
- Data mining
Hyperspectral mineralogy

- Challenges encountered when collecting ‘representative’ geoenvironmental samples at early life-of-mine stages
- Increasing ore deposit knowledge will assist with static and kinetic testing sample selection
- Hyperspectral data measuring VNIR and SWIR active minerals (e.g., Corescan) and TIR (e.g., HyLogger)
- Corescan: ~2,000 m can be collected per day
- Value-add opportunity by perform geoenvironmental domaining to support waste forecasting
- Identify potentially acid forming, non-acid forming and neutralising domains to enable waste management through early forecasting of geoenvironmental characteristics
<table>
<thead>
<tr>
<th>Type</th>
<th>Silicate Structure</th>
<th>Mineral Group</th>
<th>Example</th>
<th>VNIR Response</th>
<th>SWIR Response</th>
<th>TIR Response</th>
</tr>
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<tbody>
<tr>
<td>Silicates</td>
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</table>

Source: Linton et al. (2018)
Hyperspectral mineralogy

- Core photography
- Mineral Class map
- Chlorite wavelength position
- Chlorite match intensity
- Geotechnical parameters
Hyperspectral mineralogy

Mixed pixels are classified based on the most abundant spectra.

Core photography | Mineral map | Carbonate match

Class map colour index
- Aspectral
- Quartz/silica
- Quartz-carbonate
- Carbonate
- Sericite
- Sericite + chlorite
- Chlorite
- Clinohlore

Carbonate match
- Low match
- High match
Hyperspectral mineralogy

Core photography  Mineral class map  Sulfide distribution  Log Sulfide distribution
Hyperspectral mineralogy

Hyperspectral data

Core images

Mineral maps

Geoenvironmental Domaining Index (GDI)

Scaled Neutralising Potential/Acid Potential values

Relative reactivity values

(Jambor et al., 2007; Parbhakar-Fox and Lottermoser, 2014)

(Sverdrup, 1990)

Example

Chlorite: 60 %  * 0.006  * 0.02 = 0.00012
Carbonate: 30 %  * 1  * 1 = 30
Quartz: 10 %  * 0  * 0.004 = 0

Pixel GDI = ~30

Jackson et al. (2018)
First pass **GDI (V2)** value risk assessment with sulfides identified defines 5 risk grade classification fields

<table>
<thead>
<tr>
<th>GDI value</th>
<th>GDI risk grade</th>
<th>Description of geoenvironmental characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>-35,000 to -900</td>
<td>Extreme risk</td>
<td>Dominance of acid forming minerals. Sulfides identified as first mineral &gt; 75 %. No primary neutralisers (AP &gt;&gt;NP).</td>
</tr>
<tr>
<td>-900 to 0</td>
<td>High risk</td>
<td>Sulfides common. Sulfides identified as 2nd and 3rd mineral &lt; 75 %. No primary neutralisers (AP &gt;NP).</td>
</tr>
<tr>
<td>0 to 10,000</td>
<td>Potential risk</td>
<td>Dominated by silica/quartz, sericite, chlorite. Few sulfides present, minor primary neutralisers (AP≠NP). Some gypsum present.</td>
</tr>
<tr>
<td>10,000 to 40,000</td>
<td>Low risk</td>
<td>Carbonate abundance &lt; 50 % (AP&lt;NP).</td>
</tr>
<tr>
<td>40,000 to 100,000</td>
<td>Very low risk</td>
<td>Carbonate dominates as first Corescan mineral &gt; 50 %. Long term acid neutralising capacity likely (AP&lt;&lt;NP).</td>
</tr>
</tbody>
</table>

Jackson et al. (2018)
Hyperspectral mineralogy

Sample A: Skarn

Core photography

Classified mineral map

Sulfide recognition

Carbonate identification

GDI V2: 34,370
Low risk

Static testing= NAF (High ANC)

Jackson et al. (2018)
Sample B: Skarn

Core photography

Classified mineral map

Chlorite dominated

Sulfide recognition

Carbonate identification

GDI V2:
1910
Potential risk

Static testing=
NAF (3% sulfide-sulfur; 23% calcite)

Jackson et al. (2018)
Sample C: Porphyry Au-Cu (Potassic Alteration Zone)

Core photography

Classified mineral map

Sulfide recognition

Carbonate identification

GDI V2: -140=
High risk

Static testing=
PAF/AF

Jackson et al. (2018)
Hyperspectral mineralogy

Additional applications when scanning column feed materials prior to kinetic testing – results to be published later in 2019.
Handheld tools and chemical tests

- Environmental logging
- Chemical staining
- Hardness measurements
- pXRF
- Field chemical tests

Integration of results provides the best quality information to feed into the geometallurgical matrix.

Not all are new, but not routinely applied for geoenvironmental characterisation.
Handheld tools and chemical tests

Acid Rock Drainage Index (ARDI)

- Sulphide content: *(0 to 10)*
- Sulphide alteration: *(0 to 10)*
- Sulphide morphology: *(0 to 10)*
- Carbonate content: *(−5 to 10)*
- Mineral association: *(−5 to 10)*

Parbhakar-Fox et al. (2011; 2018); Opitz et al. (2016); Cornelius et al. (2017)
Mineral hardness to determine rate of weathering and predict elution of acid/neutralisation.

Parbhakar-Fox et al. (2015)
Handheld tools and chemical tests

Alizarin Red-S (2g) + Potassium Ferricyanide (2g)

250 ml HCl (2%)

Apply several coats of stain

calcite: red
ferroan dolomite: blue

Acid Neutralising capacity (kg H₂SO₄/t)

Depth (m)

High ANC

Staining

XRD

EPMA

CaCO₃

MgCO₃

FeCO₃

Parbhakar-Fox et al. (2015)
Automated mineralogy

Mineral Liberation Analyser

Current practice: Application in predictive ARD characterisation testwork and tailings characterisation

Target sulphide phases & characterise grain properties

SPL Lite

Buckwalter-Davis (2013): Six tailings samples New Caloumet mine, Canada

XBSE

Characterise grain properties for mineral of interest and examine associations

GXMAP

Aranta (2010): 4 waste rock samples, Antamina Mine, Peru

Parbhakar-Fox (2012): 10 waste rock samples, Lode-Au mine, 9 IOCG samples, Australia

Edraki et al. (2014): Cu-Au porphyry tailings

Commonly used techniques do not allow for low-cost high volume analysis- can XMOD be used?
Automated mineralogy - tailings fingerprinting

30 mins

FEI Quanta 600

XMOD

BSE image + 'dot' image → eCognition

Surface Area

<table>
<thead>
<tr>
<th>Carbonate Phase</th>
<th>Sulphide Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area</td>
<td>Surface area</td>
</tr>
<tr>
<td>Relative reactivity</td>
<td>Relative reactivity</td>
</tr>
<tr>
<td>AP/NP value</td>
<td>AP/NP value</td>
</tr>
</tbody>
</table>

Σ Carbonates  
Σ Sulphides

CARD RISK RATIO

Parbhakar-Fox et al. (2017)

- Extreme Risk: < 0.1
- High Risk: < 0.5
- Moderate Risk: < 1
- Potential Risk: 1-3
- Low Risk: > 3
- Very Low Risk: > 10
Data mining and machine learning

Opportunity to enhance waste domaining e.g., using Ca and Mg from assay (Jackson et al., 2019)

Extract more information from existing data sets e.g., mineralogy and texture (Cracknell et al., 2018)

Calculate mineralogy using assay data (e.g., Berry et al., 2015; Beavis et al. 2017; Howard et al., 2019)
High-res drill core image

Data mining and machine learning

Article
Automated Acid Rock Drainage Indexing from Drill Core Imagery

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3 Geoscan Pty Ltd, 11437 Grahamstown Road, Aztec, WA 6034, Australia; ekaterina.savinova@geoscan.com.au
‘Next gen’ technologies

X-ray tomography + XRF
Orexplore core scanning – structural features, ore and gangue phase morphology
(200 µm voxel resolution)

Sulphide distribution - Sunrise Dam

Pyrite – Rio Blanco tourmaline breccia Cu deposit

3D A-ARDI assessments
Additional uses of geometallurgy data and tools

Forecast the potential for future mine wastes to fix atmospheric CO₂ (using TIR data): Develop GHG consumption index.

Identify ‘soft’ zones based on classified mineralogy:
   Predictive dust characterisation protocol.

Spent heap leach materials: identify and characterise post-leach mineralogy (e.g., alunite-group).

Spent heap leach pile, Croydon Au-mines, QLD
Mine waste: Ore bodies of the future

New cobalt resources

Tin and gold from historic tailings

Zinc from slag

New indium resources?

Redrawn from MRT (2001)
Mine waste: Ore bodies of the future

Planning to return and drill up to 5 drill holes @ 60 m depth perform geomeballurgical and geoenvironmental testwork
‘Enviro’ opportunities in geometallurgy

“Transform how explorers and miners **plan and predict mining and environmental activities**, by providing new tools to guide these activities from the initial discovery through to end of mine life”

- Mineralogical & chemical data analysis to predict AMD characteristics
- ‘Next gen’ technologies and new chemical testing
- Sensor-based waste assessments during operational stages
- Tailings ‘fingerprinting’ during deposition
- Characterisation of historic mine sites and waste to determine reuse
- New assessment tools and processing approaches
Thank you

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What is ‘geometallurgy’?

- Through an integrated approach geometallurgy establishes 3D models which enable NPV optimisation and effective orebody management, while minimising technical and operational risk to ultimately provide more resilient operations.

- Critically, through spatial identification of variability, it allows the development of strategies to mitigate the risks related to variability (e.g., collect additional data, revise the mine plan, adapt or change the process strategy, or engineer flexibility into the system).

- To achieve these goals, development of innovative technologies and approaches along the entire mine value chain are being established.

- Geometallurgy has been shown to intensify collaboration among operational stakeholders, creating an environment for sharing orebody knowledge, leading to the integration of such data and knowledge into mine planning and scheduling.

- Companies that embrace the geometallurgical approach will benefit from increased net present value and shareholder value.

Dominy et al. (2018)