Real-Time Geometallurgy
FROM EXPLORATION TO REMEDIATION

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WHAT IS GEOMETALLURGY?

Combined discipline of earth and materials sciences to study and define the relationship and variability of

- physical and chemical characteristics of “Ore Types”, and
- their response to blasting, metallurgical processing, and tailings management

Includes components of both

- “Predictive metallurgy” — design of the process flow sheet during pre-feasibility studies
- “Diagnostic metallurgy” — later troubleshooting of recovery problems during production

Primary output is a “Geomet Model” for an ore body
GEOMET MODELS

- 4D model of orebody, with each mining block oriented spatially for mine planning, flowsheet design, blending strategies and optimal operations
- Aim to predict the metallurgical performance of the various ore types
- Maximize metal recoveries on a block-per-block basis over the mine life
- Confirm Mineral Resource Model and minimize risk
MINE WASTE MANAGEMENT

- Characterization of mine wastes for Acid Rock Drainage and Metal Leaching (ARDML) potential
- Can divide waste-rock lithologies into ‘geo-waste’ units based on their likely behaviour during weathering, analogous to the geomet ore types defined for mineral processing, using drill core from exploration program

Based on:
- Primary lithology
- % of acid generating sulfide minerals vs. acid neutralizing carbonate minerals
- Degree of alteration and oxidation

Screenshot of drill-hole data where different colours represent different geo-waste units.

Brough et al (2013)
Ore characteristics have direct implications for metallurgical behavior

- Degree of mineral liberation expected for
  - the given grinding capacity available
  - mineral size and shape
  - mineral hardness
  - mineral cleavage and fracture patterns
  - nature and scale of intergrowth associations

- Particle density and flotation selectivity

- Magnetic susceptibility

- Chemical reactivity and leachability

- Potential for producing deleterious penalty metals (environmental penalties) & recovering bonus credit (value-added metals)
MINERALOGY AND MINERAL ASSOCIATIONS ARE KEY INPUTS – BOTH FOR THE ORE AND GANGUE

- For some ore bodies (e.g., iron ore), it is more useful to use silicate gangue minerals as the basis for defining ore types.
- E.g., in this example, the amphibole ore-type is widespread in the magnetite ore and is a harder rock type than the feldspar ore-type, which is common in hematite.
- Biotite tends to enrich in fine size fraction during grinding, enriching silica content in the concentrate.

A geometallurgical ore type (GEM-type) classification scheme of the gangue mineralogy of Malmberget iron ore.

Lund et al. 2013
Characterize range of intergrowths that grains of specific ore minerals present within composite mineral particles.

Geomet ore types consist of one or more intergrowth textures with common grindability.

Requires digital analysis of representative number of particles imaged by optical and/or electron microscopy.
How can real-time analyses for geometallurgy maximize project income?
Modern Techniques for Quantitative Mineralogy and Texture of Ore Types and Waste Units
## TECHNIQUES FOR QUANTITATIVE MINERALOGY

<table>
<thead>
<tr>
<th>TECHNIQUE</th>
<th>METHOD</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
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</thead>
<tbody>
<tr>
<td>Digital optical microscopy</td>
<td>Image acquisition &amp; analysis software (Zeiss AxioVision, CSIRO Mineral and Recognition)</td>
<td>Semi-automated; Low capital cost &amp; operation; Mineralogy &amp; texture data</td>
<td>Limited sample throughput; Classification of low reflective minerals difficult</td>
</tr>
<tr>
<td>Integrated BSE &amp; EDX scanning electron microscopy (SEM)</td>
<td>Image acquisition &amp; analysis software (FEI QEMSCAN &amp; MLA, Oxford INCAMineral, Tescan TIMA, Zeiss Mineralogic Mining)</td>
<td>Automated; Systematically provides complex data for mineralogy and texture for all ore types</td>
<td>High capital cost &amp; operation; Sized samples preferred; Fast turnaround times of results difficult</td>
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<tr>
<td>Quantitative XRD</td>
<td>Rietveld refinement (various capable instruments – Agilent, PANalytical, Rigaku, Shimadzu, Olympus)</td>
<td>Definitive mineral ID; Modest capital cost; May be integrated with XRF for mineral chemistry</td>
<td>10% accuracy relative for mineral abundances; No textural data; Complex spectra can limit throughput</td>
</tr>
<tr>
<td>Hyperspectral imaging</td>
<td>Integrated digital imaging and reflectance spectroscopy (CSIRO/ FLSmidth HyLogging, Corescan Hyperspectral Core Imager, Norsk Elektro Optikk HySpex, Photonic Knowledge Core Mapper)</td>
<td>Low operation costs; Reasonable analysis times; Little sample preparation; Provides reliable data for mineralogy &amp; texture at macroscopic scales</td>
<td>Mineral ID and textural data poor at fine scales (&lt;1mm); Semi-quantitative mineral abundance data; High capital cost for automated core scanners</td>
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<tr>
<td>Laser Raman imaging</td>
<td>Raman spectroscopy made using a fine laser beam as excitation source stepped across a sample surface (Renishaw StreamLine Plus)</td>
<td>Definitive mineral ID; Micron-scale resolution; Images show mineral textures; Non-destructive</td>
<td>Commercial systems not tailored to geometallurgy, so suitability poorly defined</td>
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<tr>
<td>X-ray computed microtomography (XMT)</td>
<td>Attenuation of X-rays during stepwise sample rotation (SCANCO Medical AG and SkyScan Micro-CT)</td>
<td>Produces 3D images of internal structure and mineralogy of sample at a resolution of several microns; Non-destructive</td>
<td>High capital cost; Long analysis times &amp; slow throughput; Difficult to distinguish common ore minerals of similar density</td>
</tr>
<tr>
<td>Mineralogy calculated from mineral and bulk sample assays</td>
<td>Mass balance algorithms based on chemistry measured by XRF, EPMA, ICPMS, Laser ablation/ionization, LIBS, PGNAA, APXS</td>
<td>Fast, inexpensive, cost effective; High throughput possible</td>
<td>Variable mineral chemistry can produce errors; No information about mineral textures, associations, sizes &amp; shapes</td>
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</table>
Software based on advances in:

- Automated image acquisition
- High resolution cameras for digital imaging
- Integration of multiple optical image layers
- Image analysis techniques
  
  - Automated texture classification for every particle or image frame according to user-defined classification scheme
  - Calculation of mineral composition, chemical assay, density, dimensional or textural characteristics for every particle
  - Calculation of liberation and association data for specified minerals
  - Results can be integrated with SEM images and mineral classifications

SEM-BASED IMAGE ANALYSIS

- Mature technology; >200 instruments worldwide, mostly in industry
- Utilizes backscattered electron (BSE) imaging for phase discrimination and energy dispersive x-ray (EDX) analysis for mineral identification
- Provide sophisticated automation and extensive data outputs: modal mineralogy, calculated assay, element distribution, mineral grade recovery, element grade recovery, particle size distribution, mineral grain size distribution, particle density distribution, mineral association, mineral locking, phase specific surface area, mineral liberation

![BSE grey level distribution of some common minerals](image)

![X-ray particle mapping](image)

Fandrich et al (2007)
RIETVELD QUANTITATIVE X-RAY DIFFRACTION

- Whole-profile-fitting for each specific phase in an X-ray diffraction pattern
- Theoretical crystal structure factors form Gaussian peak shapes for each phase, subtracted from total XRD spectrum
- “Difference pattern” obtained by subtracting the known phases is used to isolate remaining and/or overlapping peaks for ID of unknown phases
- Modal abundances accurate to ±10% relative; Detection of phases >1-3% in abundance
- Can be integrated with automated sample preparation for online process control

Bragg’s Law
\[ n(\lambda) = 2d \sin(\theta) \]

Raw XRD spectrum of bauxite

Kirwan et al (2009)
HYPERSPECTRAL IMAGING

- Combines digital imaging (RGB color camera) and reflectance spectroscopy (visible, near infrared and in some cases shortwave IR wavelengths)
- Each pixel in an image contains the light intensity for several hundred, narrow adjacent spectral bands – so all pixels in an image contain a continuous spectrum
- Mineral ID determined on a pixel-by-pixel basis by spectrum matching to reference mineral standards
- Mineral abundance inferred from sizes of absorption troughs and peaks
- Results can be verified by XRF and XRD
- Textural information at the pixel size of the camera (~0.1mm) and spectrometer (~0.5mm)
- Some instruments designed as a production tool, scanning 100–400m of core in 10-hours at 25–100mm resolution.

Haest et al (2012)
LASER Raman Imaging

- Based on a small fraction of laser light incident on minerals being scattered at wavelengths characteristic of their structure, allowing them to be identified definitively.
- Can use IR, visible and UV laser wavelengths so almost all minerals can be identified.
- An image of the minerals in a sample volume may be created by using a tightly focused excitation laser beam to generate a Raman spectrum at a single spot in the sample, then to use a scanning mechanism to move to another sample spot.
- In development for planetary science missions, not yet applied for geometallurgy.
- Can be applied to drillcore or chips with flat-cut surfaces, thin sections, grain mounts; even fluid inclusions.
- Micron or better spatial resolution.

Wang et al (2014)
X-RAY COMPUTED MICRO-TOMOGRAPHY (XMT)

- X-rays traverse the sample and are attenuated as a function of density and atomic number, which can be related to mineral ID.
- Intensity of attenuated X-ray signal converted by a scintillator into light and recorded as a radiographic 2D digital image.
- Sample is rotated by small angular steps, each producing a 2D radiograph, which a computer reconstructs to render a 3D tomogram.
- Full scan of a small piece of core takes several hours at 5 micron resolution.
- Emerging technology, mainly applied to rare phase searches (gold, PGMs).
- Recently used to produce 2D images of sized grains mounted on a slide by irradiating at two energy levels (dual energy analysis).
- Greatly reduces analysis times (200,000 particles measured in <1 h).
Element to mineral conversion is based on a set of linear algebraic equations where the bulk chemical composition of a sample is converted to mineral grades using a set of least-squares equations. This can be expressed as an equation

\[ A \times x = b \]

where A is a table giving the weight fractions of elements in the minerals (e.g. electron microprobe analyses, known), the x vector is the weight fractions of the minerals in a sample (unknown) and the b vector is the weight fraction of elements in the sample (known).

Main uncertainty is the inventory of minerals assumed to be present in the samples and the variability of their compositions
WHEN CAN REAL-TIME ANALYSIS BE MADE FOR GEOMETALLURGY?

“EARLY”: Drill core/chip analysis for predictive metallurgy, advanced exploration, feasibility study and mine planning

“LATER”: Analysis of process feed for monitoring operations, diagnostic metallurgy and tailings management
<table>
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<tr>
<th>TECHNIQUE</th>
<th>“EARLY” (DRILLCORE/CHIP)</th>
<th>“LATER” (PROCESS FEED)</th>
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<tr>
<td>Digital optical microscopy</td>
<td>Each sample of core or chip must be cut and polished. Core scanning not practical</td>
<td>On-line conveyor belt analysis not practical. Sub-samples must be prepared/analyzed off-line</td>
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<tr>
<td>Integrated BSE &amp; EDX scanning electron microscopy (SEM)</td>
<td>Each sample of core or chip must be cut and polished, and sized grain fractions preferred. Core scanning not practical</td>
<td>On-line conveyor belt analysis not practical. Sub-samples must be prepared/analyzed off-line</td>
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<tr>
<td>Quantitative XRD</td>
<td>Requires each sample powder to be mounted on slide. Core scanning not practical</td>
<td>On-line conveyor belt analysis not practical. Sub-samples must be prepared/analyzed off-line</td>
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<td>Hyperspectral imaging</td>
<td>Core scanning well developed</td>
<td>On-line conveyor belt analysis not practical. Sub-samples must be prepared/analyzed off-line</td>
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<tr>
<td>Laser Raman imaging</td>
<td>Each sample of core or chip must be cut and polished. Core scanning possible but not yet developed</td>
<td>On-line conveyor belt analysis not practical. Sub-samples must be prepared/analyzed off-line</td>
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<tr>
<td>X-ray computed microtomography (XMT)</td>
<td>Little sample preparation required. Core scanning not practical</td>
<td>On-line conveyor belt analysis not practical. Sub-samples must be prepared/analyzed off-line</td>
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<td>Mineralogy calculated from mineral and bulk sample assays</td>
<td>Core scanners are developed for lithogeochemistry, but sub-samples need separate analyses (EPMA, micro-XRF, LIBS) for mineral chemistry</td>
<td>On-line conveyor belt analysis are developed for lithogeochemistry (LIBS, PGNAA), but sub-samples need separate analyses (EPMA, micro-XRF, LIBS) for mineral chemistry</td>
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Accuracy of geo metallurgical models would be improved by wider application of real-time analyses

- Existing hyperspectral drill core scanners should be integrated with other techniques (Raman imaging?) to verify and (where necessary) refine results

- Process feeds on conveyor belts cannot be reliability measured on-line, in real-time for mineralogy (at the present time)
  
  • *Real-time geochemical analyses (by LIBS, PGNAA) can be used however to calculate mineralogy*
  
  • *These results should be supplemented by analyses of sub-samples for mineral associations, textures and grain morphology using other techniques that can be deployed at the mine site*