Geometallurgy basics
for mineral processing applications

Introduction
Presented by: Alex Doll, Consultant
Most important concept!

ALL MODELS ARE WRONG, BUT SOME ARE USEFUL.
Geometallurgy

• Geometallurgy and **grinding**
  – It is often desirable to be able to load ore hardness information into the mine block model.
  – Allows the mining engineers to better schedule ore delivery to the plant, and to run more sophisticated net present value calculations against ore blocks.
  – Requires hundreds of samples from drill holes distributed across the orebody.
Geometallurgy

• Geometallurgy and **plant recovery**
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  – Requires hundreds of samples from drill holes distributed across the orebody.
Sampling
• Geologic systems can be modelled as a structure of equally sized blocks arranged in a regular grid.

source: GEOVIA Surpac brochure
Interpolation

• Interpolation is the mathematical method used to estimate a parameter in the spaces between known positions with known values.
  – A simple interpolation method could be a linear weighted average of the two nearest points.
  – Geostatisticians use more complex methods, such as kriging.
Interpolation

- Consider the same 1-dimensional model with measurements at points A&B.

- Try an inverse-distance-squared weighting.

\[
X = \frac{(1/10)^2 \times A + (1/23)^2 \times B}{(1/10)^2 + (1/23)^2}
\]

\[
X = 1.16 \text{ g/t}
\]
Interpolation

• Consider a 3-dimensional model with measurements at points A, B, C, D
• A 'polygon' displays the rock unit that X belongs to.
Interpolation by kriging

- The most common interpolation is some form of kriging.
- Kriging uses non-linear, directional interpolation constrained by domains.
Check the domains

• Domains determined for assay data may not apply for process parameters
• Geostatisticians should re-domain the process data to verify.

• Example: Grade may be determined by alteration, but grindability may be determined by tectonic stress fields.
• You must check!
Domains

- Example grinding data, top from a 'hematite' domain and bottom from a 'magnetite' domain.
- Shapes are different – confirms each must be interpolated separately.
Example domain definitions

- Collahuasi, Chile
  - C. Suazo, Procemin 2011

- C. Suazo, Procemin 2013

<table>
<thead>
<tr>
<th>UGM</th>
<th>alteration</th>
<th>lithology</th>
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<tbody>
<tr>
<td>1</td>
<td>1° sericite, argillic, Chl-Ser</td>
<td>intrusive</td>
</tr>
<tr>
<td>2</td>
<td>1° sericite, argillic, Chl-Ser</td>
<td>host rock</td>
</tr>
<tr>
<td>3</td>
<td>1° qtz-ser, propylitic, biot, K</td>
<td>intrusive</td>
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<tr>
<td>4</td>
<td>1° qtz-ser, propylitic, biot, K</td>
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<tr>
<td>6</td>
<td>2° qtz-ser, propylitic, biot, K</td>
<td>intr.+host</td>
</tr>
</tbody>
</table>
A variogram plots the average difference between two arbitrary points and the distance between the points.
Variogram

• Warning: *oversimplified*!!!

• Plotting the example grade difference vs. distance from earlier slide
• Slightly more correct version

• Y-axis shows variance

• The population variance is shown as the “sill”
Variogram

- A published variogram from Adanac Moly suggests that the maximum spacing between samples should be 200 m or less.

– Bulled, CMP 2007
How many samples?

• Area of influence of a sample
  – How “close by” must a sample be to have importance in geostatistics.
  – Observed as the location of the “sill” of a variogram of grindability versus distance.
  – So you should know the variogram result of a geometallurgy program to plan a geometallurgy program.
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Additive parameters
Additivity

• Geostatistics only works if the values you are “mixing” have a linear mixing characteristic.

• A parameter is “additive” if you can combine two samples of a known value, and the blend test results in the arithmetic average of the two.
  – Eg. mix one sample “10” and a second sample “20”
  – The blend should give a result of “15”
Additivities

• Values suitable for block modelling
  – Not all grindability results are suitable for block model interpolation, they must be “additive”
    • e.g. mixing two samples with “10” and “20” should give “15”. Work index, SGI and A×b results do not have this property.
  – Specific energy consumption is generally additive, so $E_{\text{total}}$, $E_{\text{SAG}}$ and/or $E_{\text{ball}}$ can be interpolated.
Additivity of process parameters

• We will look at a variety of process models in the next two days. You will need to evaluate which models are useful for your mine.
  – The process models need to make useful predictions of process behaviour.
  – The process models need to have additive parameters suitable for geometallurgy.
Geometallurgy program

• Procedure for a geometallurgy program:
  – collect samples distributed around the orebody
  – test in the laboratory, use at least 2 methods
  – run all samples through comminution models
  – distribute specific energy values into block model
  – run geostatistical checks (variograms) and repeat (do a second, in-fill, sample collection program)
  – provide mining engineers with a model populated with grindability values; run annual production forecasts.
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Mine Planning by Geometallurgy
The block model

• A block model containing geometallurgical data will include:
  – grindability information suitable for estimating the maximum plant throughput,
  – recovery information suitable for estimating the metal production,
  – (flotation plants) concentrate grade predictions for smelter contracts.
Grindability models

• Specific energy consumption models determine how much energy is required to grind a sample.
  – $E$ given in kW·h/t \{alternative notation: kW/(t/h)\}

• Mill power models determine the amount of grinding power available
  – $P$ given in kW

• Dividing $P$ by $E$ gives the circuit throughput
  – $t/h = kW \div (kW\cdot h/t)$
Throughput predictions

• Grindability, in the form of specific energy, will be interpolated for a block.
  – in this example, $E_{SAG} = 6.0 \text{ kWh/t}$

• The metallurgists will supply the typical power draw of the SAG mill (at the pinion).
  – Yanacocha is about 14,000 kW

• Throughput = $14,000 \text{ kW} \div 16.0 \text{ kW} = 875 \text{ t/h}$
Recovery models

\[ R = R_{\text{max}} \times (1 - e^{-kt}) \]

Recovery curves, \( R_{\text{max}} = 0.99 \)

Recovery curves, \( R_{\text{max}} = 0.80 \)
Net Smelter Return prediction

• The mining engineer can estimate the revenue of a block using the recovery equation(s) and the block model parameters.
  – Gold recovery $R$ is known by interpolation.
  – Revenue=block mass (t) × grade (g/t) × recovery

• If there are penalty elements in the block model, it may be necessary to estimate their recovery, too.
Block value prediction

• Determine the value of a block
  – Revenue
    • include penalties, if applicable
  – Operating costs ($/t)
    • include mill power draw, kWh/t × t/h × $/kWh
    • include other operating costs
  – Processing time can be included as a cost penalty
    • revenue form harder blocks worth less than revenue from softer blocks.
New cut-off calculation

• The variable revenue benefits blocks with good recovery characteristics.
• The variable grindability benefits blocks with lower power consumption.
• Applying a penalty for difficult to process blocks benefits easy to process blocks.
Benefits of geometallurgy

• Permits future production to be accurately predicted. Future sales can be estimated.
• Identifies “problem” areas within the mine where throughput may be low or recovery may suffer.
• Allows better optimized mine plans with more accurate NPV predictions per block.
Variable mining rate

• Operate the mine to keep the SAG mills full.
• A grinding geometallurgy database allows mine planners to schedule more ore to the mill.
  – Do not plan a “nominal” throughput rate for the whole mine life...
  – mine more in years with soft ore, and
  – mine less in years with hard ore.
  – If possible, defer hard ore until later in the mine life.
Variable gold production

• The gold production in each year of a mine life will be different, and can be calculated from
  – block gold grade,
  – block gold recovery,
  – block throughput calculated from the grindability.

• The pit optimizing software will pull the pit towards softer ore with better recovery.
Summary of benefits

- The pit shape and equipment fleet will change due to the new NPV equations,
- the pit will probably be mined more rapidly,
- production is advanced into earlier mine years,
- a more optimal pit shape will all result from a fully applied geometallurgy program, and
- no nasty surprises.
Stages of a geometallurgy program

- Decide which process parameters to collect
  - plant surveys, fitting models to plant data
- Conduct a drilling program to obtain samples of future ore
- Conduct a laboratory program determining parameters for samples
- Supply geostatisticians the parameters and their spatial locations
- Interpolate the parameters into the block model
  - check variograms, conduct in-fill drilling and recycle
- Generate a mine plan with a variable ore throughput
- Generate a cash flow with a variable gold production rate
Cost of a geometallurgy program

- Plant surveys, engineering time fitting models to plant data
- Drilling program to obtain samples of future ore
- Laboratory program determining parameters for samples
- Geostatistician time to interpolate parameters into the block model
  - Check variograms, conduct in-fill drilling and recycle
- Mine engineering time to generate a mine plan
- Sustaining capital cost of mine fleet needed to support variable throughput rates
Geometallurgy for scoping studies

- Early project evaluation will not use a full program:
  - Use about 5-15 intervals of half-core (from the resource drilling program).
  - Do laboratory work for one set of process models.
  - Unlikely enough data will exist to do variograms or kriging. Work with cumulative distributions instead of geometallurgy.
Geometallurgy for prefeasibility

• Collect at least 50 more half-core samples from the resource drilling.
  – The quantity should be sufficient to permit creation of variograms.
  – Do the first circuit of the geometallurgy program stages, but exclude the recycle.
  – Determine how much of the orebody is unrepresented by samples.
  – Do the variable rate mine plan and gold production schedule.
Geometallurgy for full feasibility

• Using the variograms from prefeasibility, determine how many more samples are needed
  – These extra samples should be dedicated metallurgical drilling. Use the whole core for a greater variety of metallurgical tests.

• Do the “recycle” loop and determine updated variable rate mine plans and gold production.
Geometallurgy for operation

• Do the program indicated for prefeasibility and feasibility to establish the initial mine plans.
• Do annual drilling to keep extending into the next 5 years of future ore.
• Revise the process models (did they work?).
• Revise the mine plans based on the updated geometallurgy database.
Examples of geometallurgy

• Los Bronces, Confluencia (Chile)
  – Design of pit for an expansion project included plant recovery and ore grindability parameters.

• Collahuasi (Chile)
  – Monthly throughput predictions are within 5% of actual.
Examples of geometallurgy

• Freeport-McMoRan study
  – Geometallurgical database used to compare SAG milling to HPGR in a detailed study.

• Andina, Piuquenes tailings (Chile)
  – Recovery and regrind energy for re-mining a tailings pond.
Escondida variograms

AZIMUTH = 0  DIP = -90
\( \gamma(h) = 0.250 + 0.377 \text{Sph}_{120.4}(h) + 0.343 \text{Sph}_{224.6}(h) \)

BWi Zones 1 + 4

AZIMUTH = 0  DIP = -90
\( \gamma(h) = 0.390 + 0.401 \text{Sph}_{108.8}(h) + 0.239 \text{Sph}_{174.6}(h) \)

mSPI Zones 1 + 4

AZIMUTH = 0  DIP = -90
\( \gamma(h) = 0.255 + 0.509 \text{Sph}_{110.6}(h) + 0.238 \text{Sph}_{221.5}(h) \)

BWi - Zones 2 + 3

AZIMUTH = 0  DIP = -90
\( \gamma(h) = 0.250 + 0.406 \text{Sph}_{120.4}(h) + 0.254 \text{Sph}_{224.6}(h) \)

mSPI Zones 2 + 3
Examples of geometallurgy

- Los Bronces, Rajos Infiernillo & Donoso Modelamiento y estimación

<table>
<thead>
<tr>
<th>UGMs de Flotación</th>
<th>UGMs SPI,BWI</th>
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Litología
Redox
Estilo Mxx
Sólidos
Textura
Estilo Mxx
Solidos

Rocha et al.
GEOMET2012
Examples of geometallurgy

• Adanac Molybdenum, Canada
  – Flotation model using interpolated parameters:
    • $k$, $R_{max}$ value for molybdenum
    • $k$, $R_{max}$ value for non-sulphide gangue
  – Different models run at different grind $P_{80}$ sizes
    • $k$, $R_{max}$ values change at each $P_{80}$. 
Final thoughts

• Grade proxies and process mineralogy are often called geometallurgy, but they are different
  – Grade proxy is where a process variable (eg. recovery) is closely related to a grade (%Cu)
  – Process mineralogy is a careful mapping of minerals (rather than elements)
    • useful to predict recoveries, rate constants, etc.
Most important concept!

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References
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– NI43-101 report, Zafranal project