Geometallurgy basics
for mineral processing applications

<u>Introduction</u>

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**
  - It is often desirable to be able to load leaching information into the mine block model.
  - Allows the mining engineers to run more sophisticated net present value calculations against ore blocks.
  - Requires hundreds of samples from drill holes distributed across the orebody.

Sampling

Block model

source: GEOVIA Surpac brochure

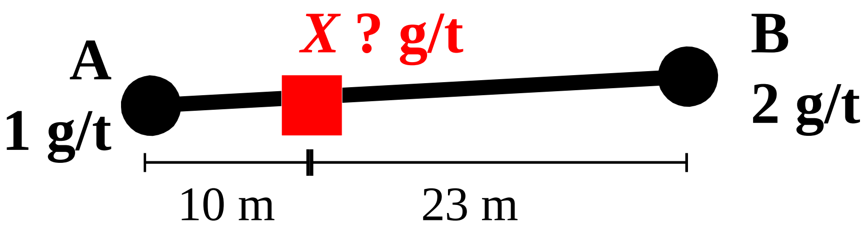
- Geologic systems can be modelled as a structure of equally sized blocks arranged in a regular grid.

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.

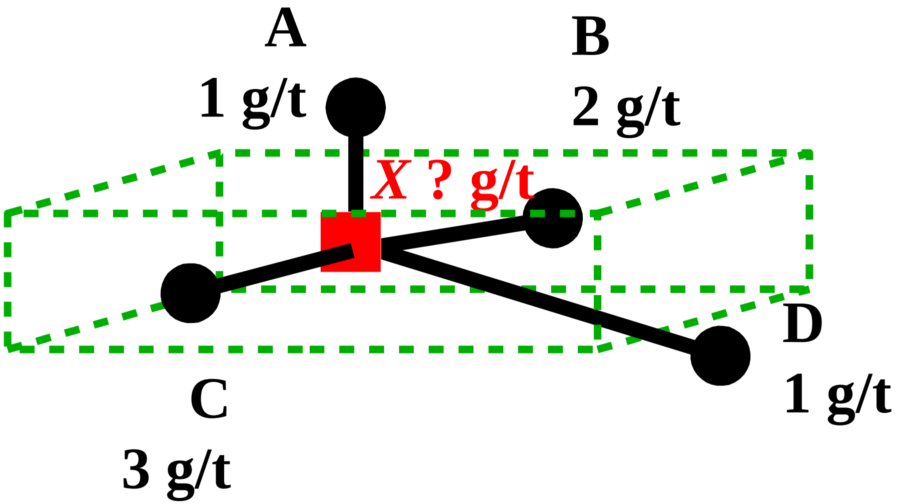


$$X = \frac{(1/10)^2 \times A + (1/23)^2 \times B}{(1/10)^2 + (1/23)^2}$$

$$X = 1.16 \text{ g/t}$$

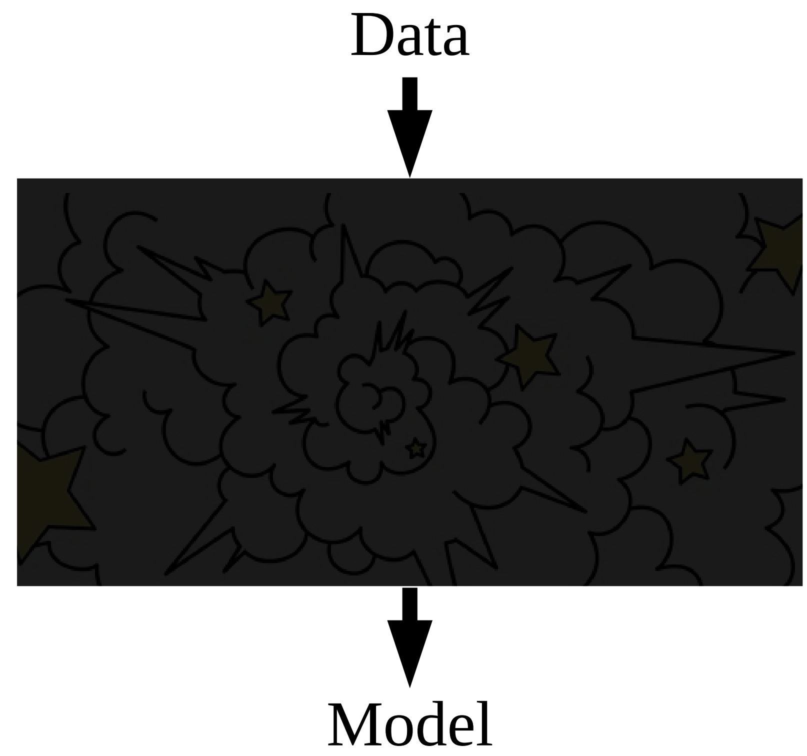
Interpolation

- 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.

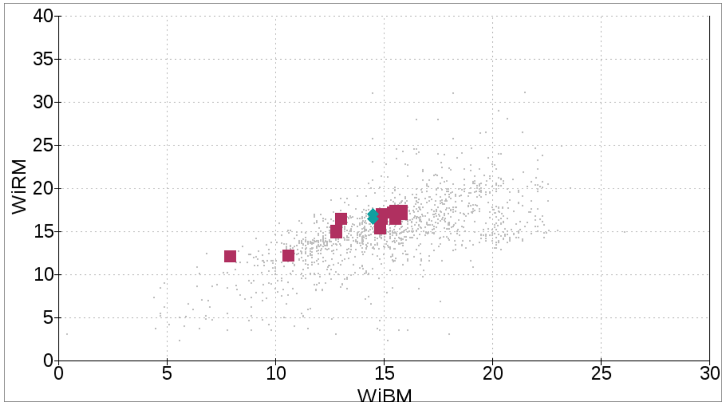


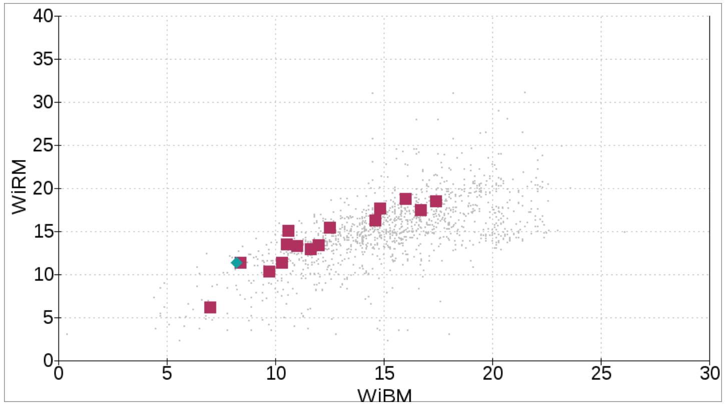
Check the domains

- 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.

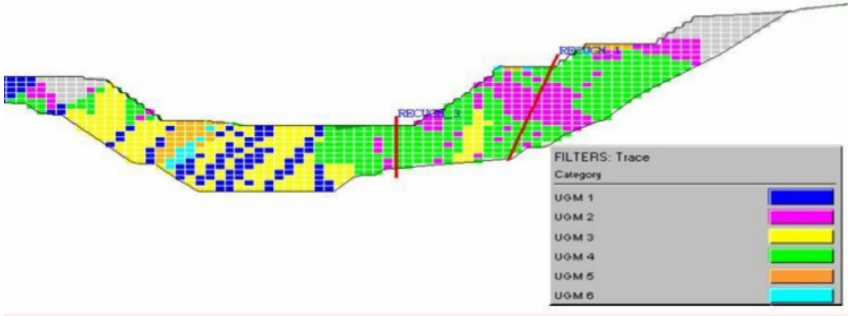




Example domain definitions

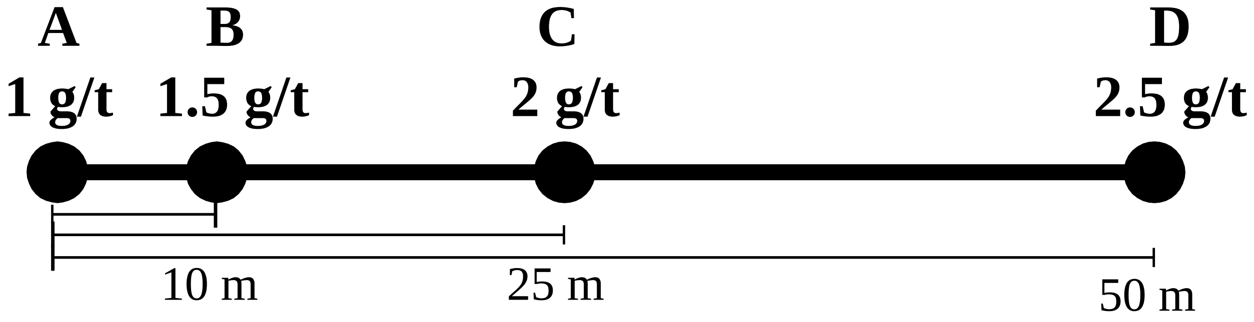
- Collahuasi, Chile
  - C. Suazo, Procemin 2011
  - C. Suazo, Procemin 2013

UGM		alteration	lithology
1	1°	sericite, argillic, Chl-Ser	intrusive
2	1°	sericite, argillic, Chl-Ser	host rock
3	1°	qtz-ser, propylitic, biot, K	intrusive
4	1°	qtz-ser, propylitic, biot, K	host rock
5	2°	sericite, argillic, Chl-Ser	intr.+host
6	2°	qtz-ser, propylitic, biot, K	intr.+host



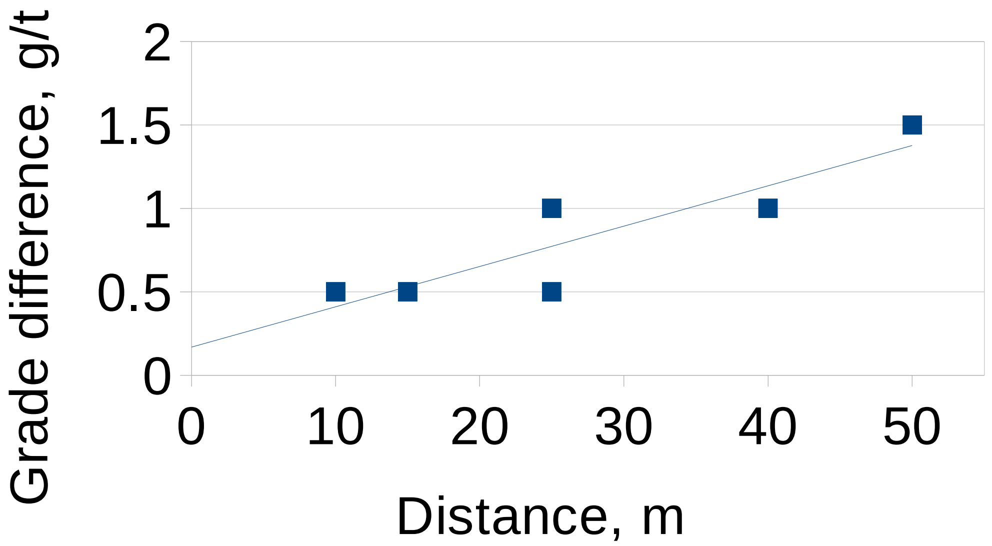
Variogram

- A variogram plots the average difference between two arbitrary points and the distance between the points.



Variogram

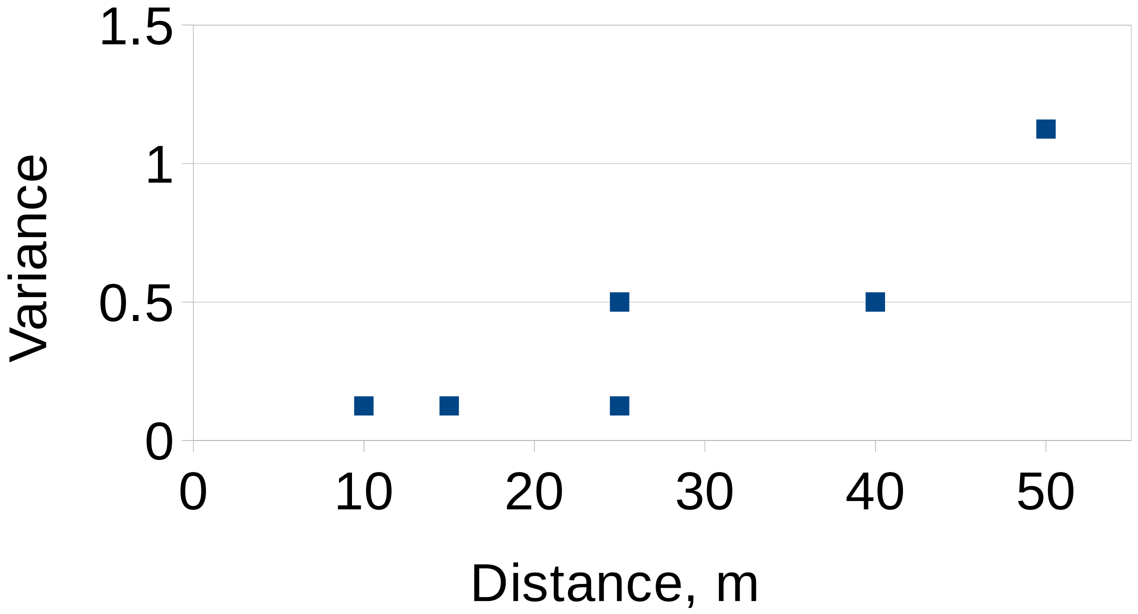
- Warning: *oversimplified!!!*



- Plotting the example grade difference vs. distance from earlier slide

Variogram

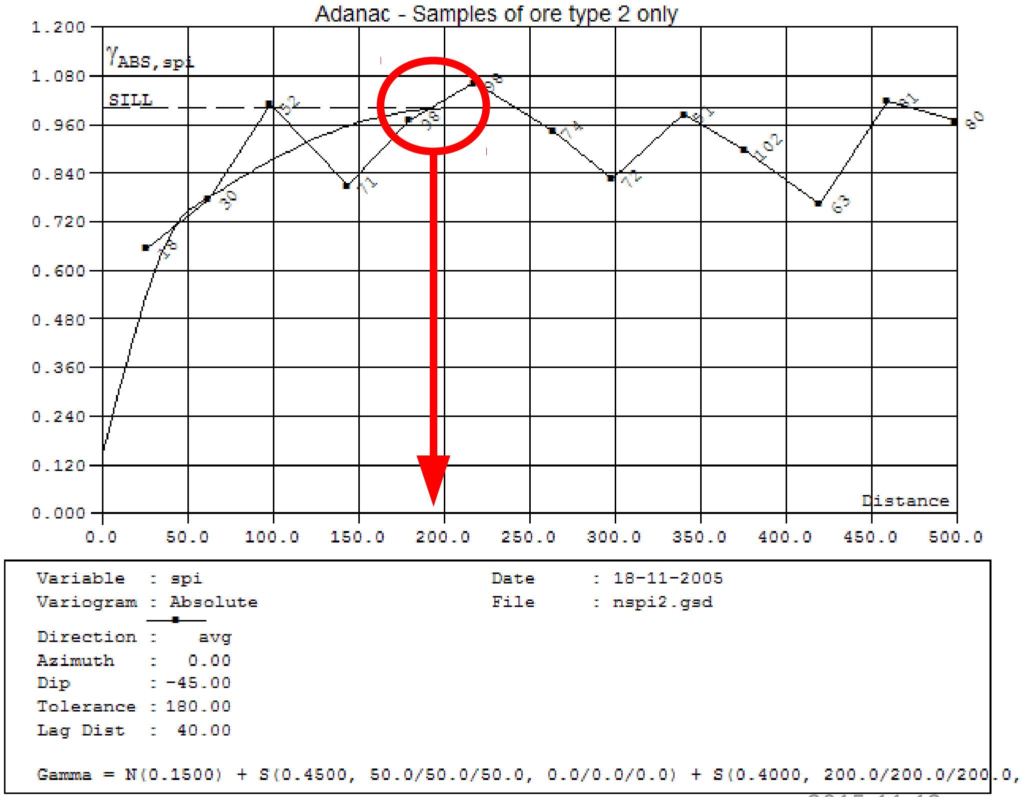
- Slightly more correct version



- 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.

Geometallurgy basics

for mineral processing applications

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"

Additivity

- 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_{total}, E_{SAG} and/or E_{ball} can be interpolated.

Additivity of process parameters

- A variety of process models exist, and you can create your own. 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.

Geometallurgy basics

for mineral processing applications

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
  - $t/h = kW \div (kW \cdot h/t)$

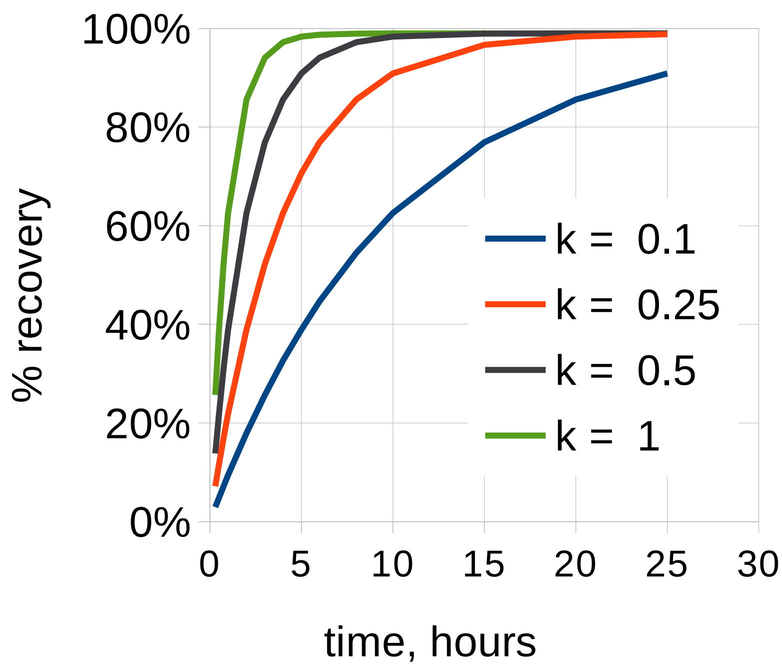
Throughput predictions

- Grindability, in the form of specific energy, will be interpolated for a block.
  - in this example, E_{SAG} = 6.0 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 kW ÷ 16.0 kW = 875 t/h

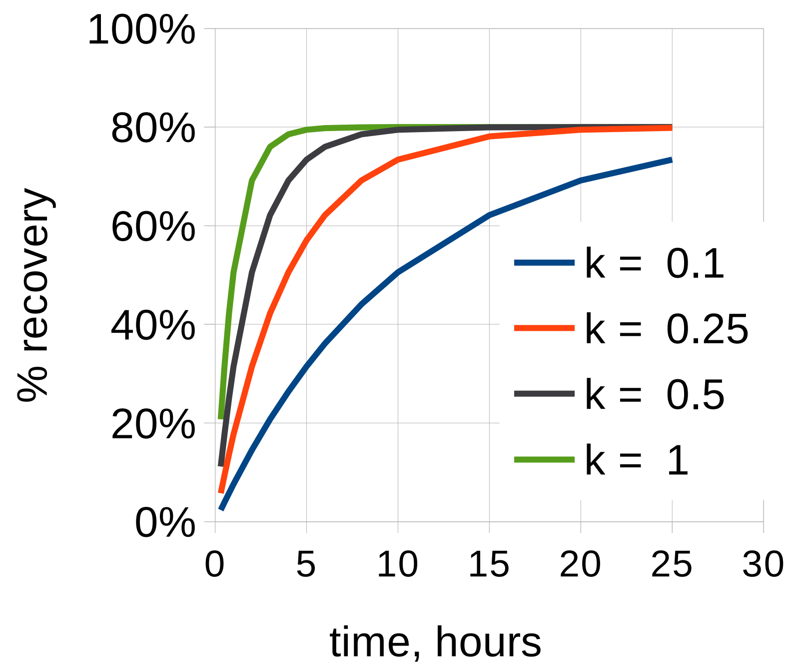
Recovery models

$$R = R_{max} \times \left(1 - e^{-kt}\right)$$

Recovery curves, Rmax=0.99



Recovery curves, Rmax=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, is 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

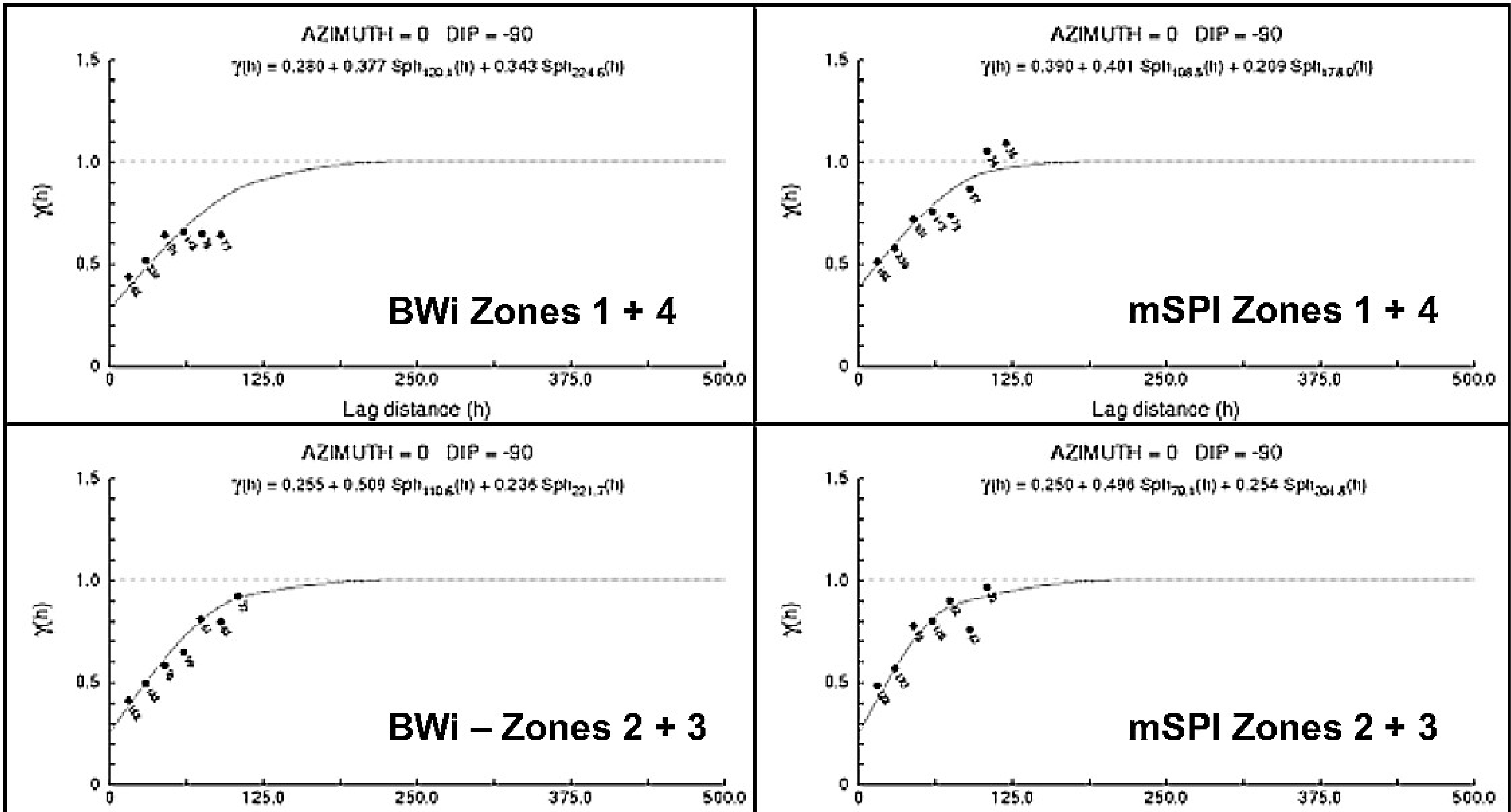
- Los Bronces, Confluencia (Chile)
  - Design of pit for an expansion project included plant recovery and ore grindability parameters.
- Collahuasi (Chile)
  - Monthly throughput predictions are within 5% of actual.

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

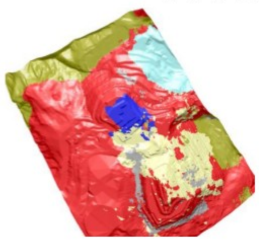
Preece, 2006

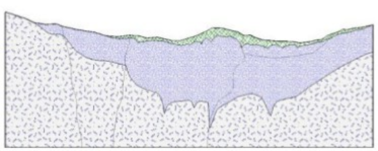


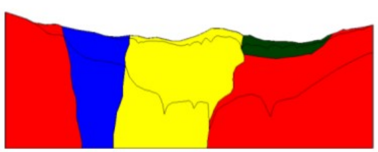
Examples of geometallurgy

- Los Bronces, Rajos Infiernillo & Donoso

Modelamiento y estimación







Unidades geometalúrgicas				
UGMs de Flotación	UGMs SPI,BWI	UGMs Crusher Index	UGMs Sulfuros Primarios	UGMs Sulfuros Secundarios
6015	20	80	6015	1
6020	40	91	6020	2
3515	80	111	3515	3
3520	91	112	3520	4
4020	101	113	4020	5
8015	102	114	8015	
9115	103		9115	
	104			
	105			
	106			

Litología	Litología	Litología	Litología	Litología
Redox	Sólidos	Redox	Redox	Redox
Estilo Mxx	Textura	Textura	Estilo Mxx	Solidos
				Indicadores

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!

ALL MODELS ARE WRONG,

BUT SOME ARE USEFUL.

Geometallurgy basics

for mineral processing applications

References

- References

  - Brissette, M. & de Souza, H. (2012) `Metallurgical testing of iron ore from the Labrador Trough`, Mineral Resources Review Conference, retrieved from http://www.nr.gov.nl.ca/NR/mines/MRR2012_LookBack/Brissette%20and%20de%20Souza%20(SGS)%20Iron%20Ore%20Metallurgical%20Testwork.pdf
  - Bulled, D. (2007) `Flotation circuit design for Adanac Moly Corp using a geometallurgical approach`, Proceedings of the 39th Canadian Mineral Processors Conference, Ottawa, Canada.
  - Preece, R. (2006) `Use of point samples to estimate the spatial distribution of hardness in the Escondida porphyry copper deposit, Chile`, Proceedings of International Autogenous and Semiautogenous Grinding Technology 2006, eds. Allan, M., Major, K., Flintoff, B., Klein, B. & Mular, A., Vancouver, Canada.

- References

  - Rocha, M., Ulloa, C. & Díaz, M. (2012) `Geometallurgical modelling at Los Bronces mine`, Proceedings of the International Seminar on Geometallurgy (GEOMET 2012), eds. Barahona, C., Kuyvenhoven, R. & Pinto, K., Santiago, Chile.
  - Suazo, C., Hofmann, A., Aguilar, M., Tay, Y. & Bastidas, G. (2011) `Geo-metallurgical modelling of the Collahuasi grinding circuit for mining planning`, Proceedings of the 8th International Mineral Processing Conference, eds. Kracht, W., Kuyvenhoven, R., Lynch-Watson, S. & Montes-Atenas, G., Santiago, Chile.

- References

  - Suazo, C., Muñoz, C., & Mora, N. (2013) `The Collahuasi geometallurgical modelling and its application to maximizing value`, Proceedings of the 10th International Mineral Processing Conference, eds. Álvarex, M., Doll, A., Kracht, W. & Kuyvenhoven, R., Santiago, Chile.
  - NI43-101 report, Zafranal project