



Geometallurgy basics

for mineral processing applications

Introduction

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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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Sampling



Block model



source: GEOVIA
Surpac brochure

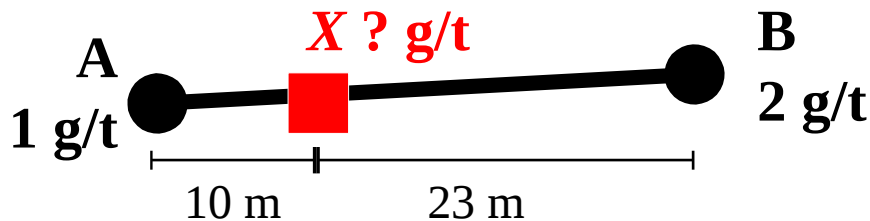
- Geologic systems can be modelled as a structure of equally sized blocks arranged in a regular grid.

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.

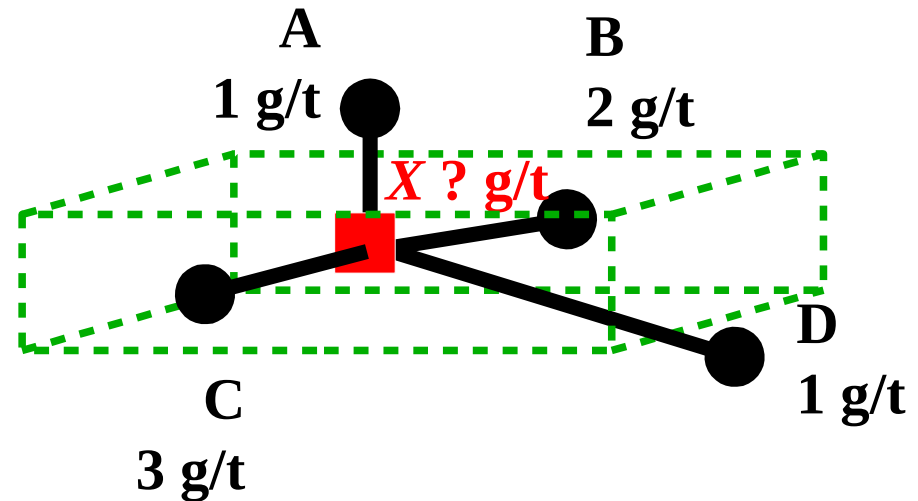


$$X = \frac{(1/10)^2 \times A + (1/23)^2 \times B}{(1/10)^2 + (1/23)^2}$$

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

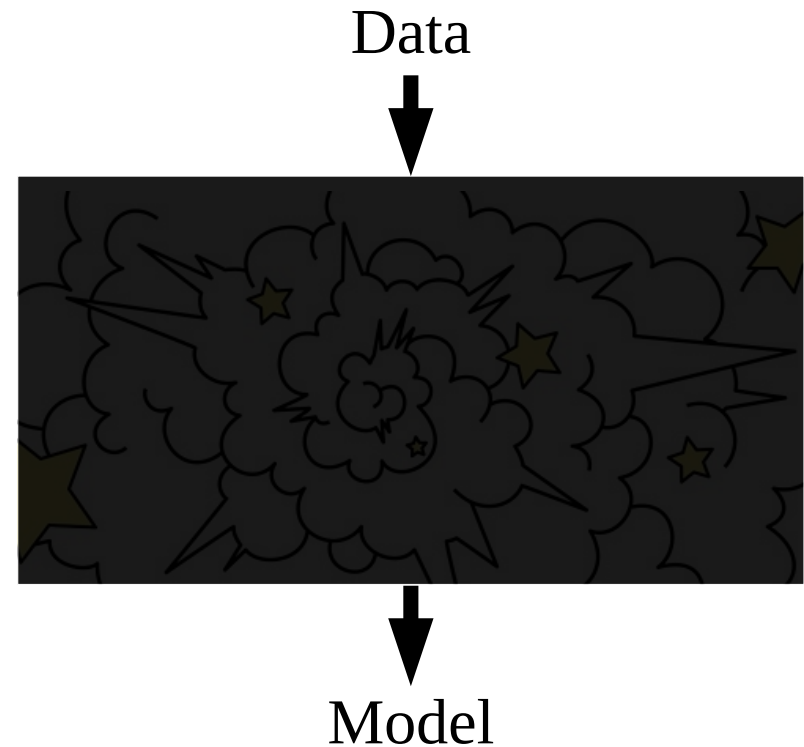
Interpolation

- 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.

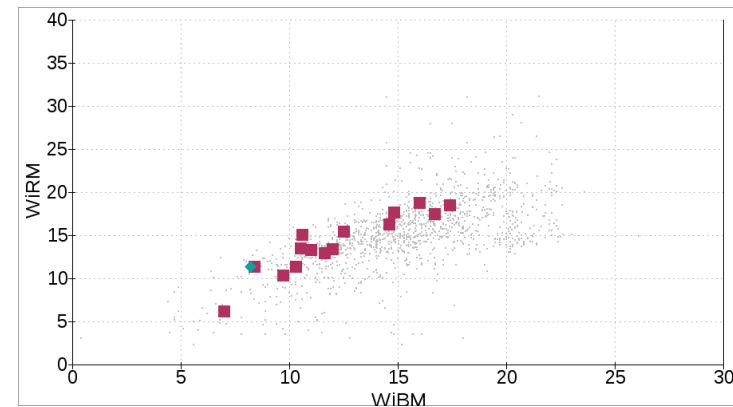
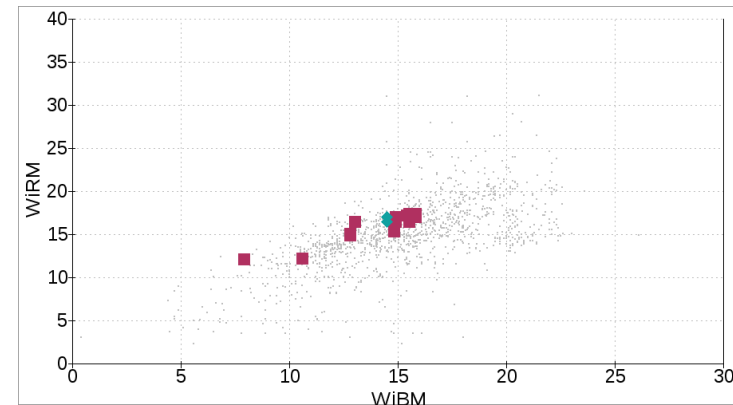


Check the domains

- 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

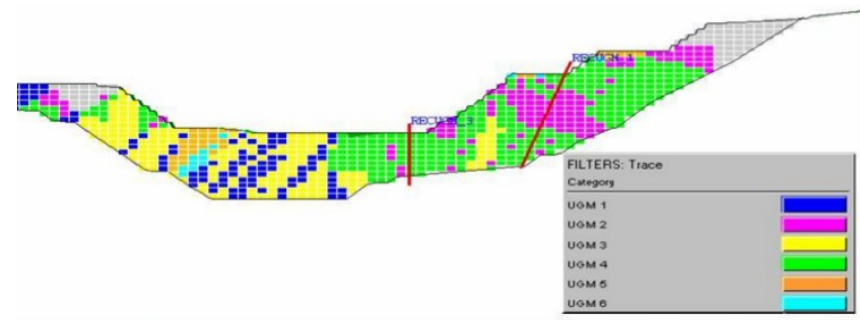
- Example grinding data, top from a 'hematite' domain and bottom from a 'magnetite' domain.
- Shapes are different
 - confirms each must be interpolated separately.



Example domain definitions

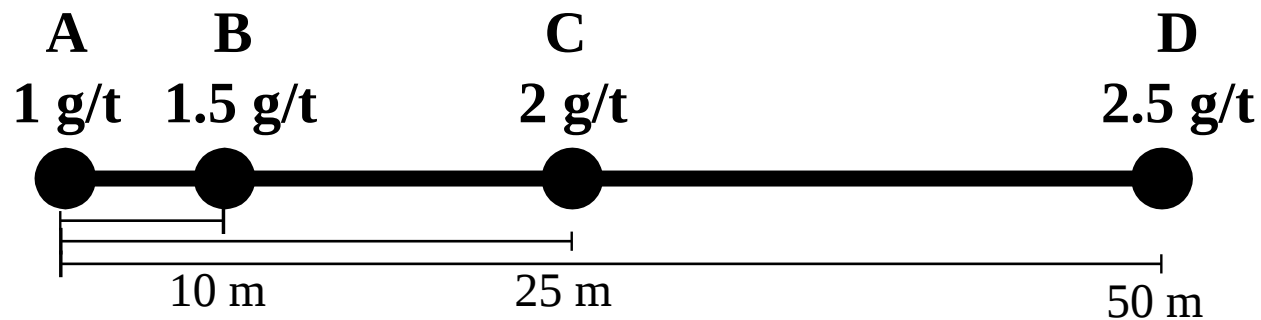
- Collahuasi, Chile
 - C. Suazo, Procemin 2011
 - C. Suazo, Procemin 2013

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



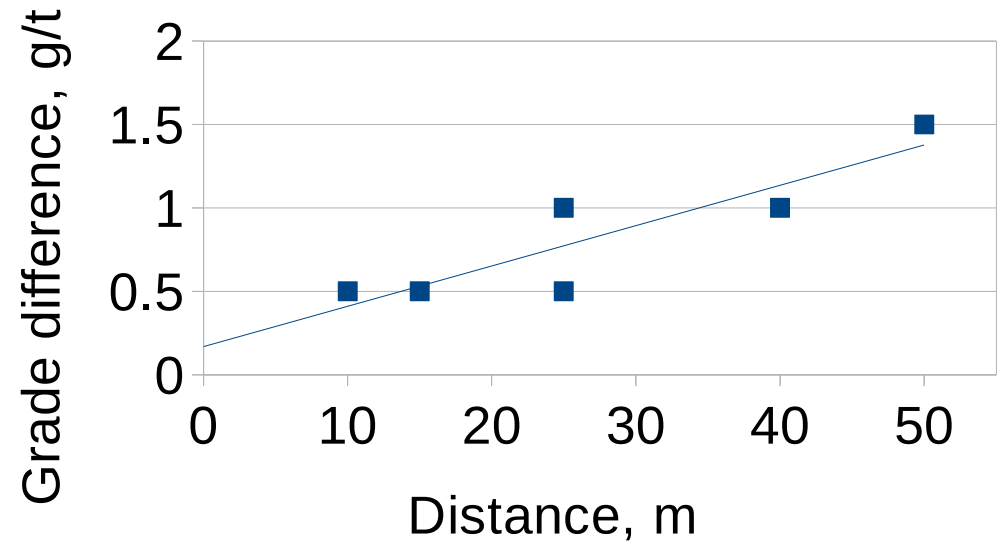
Variogram

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



Variogram

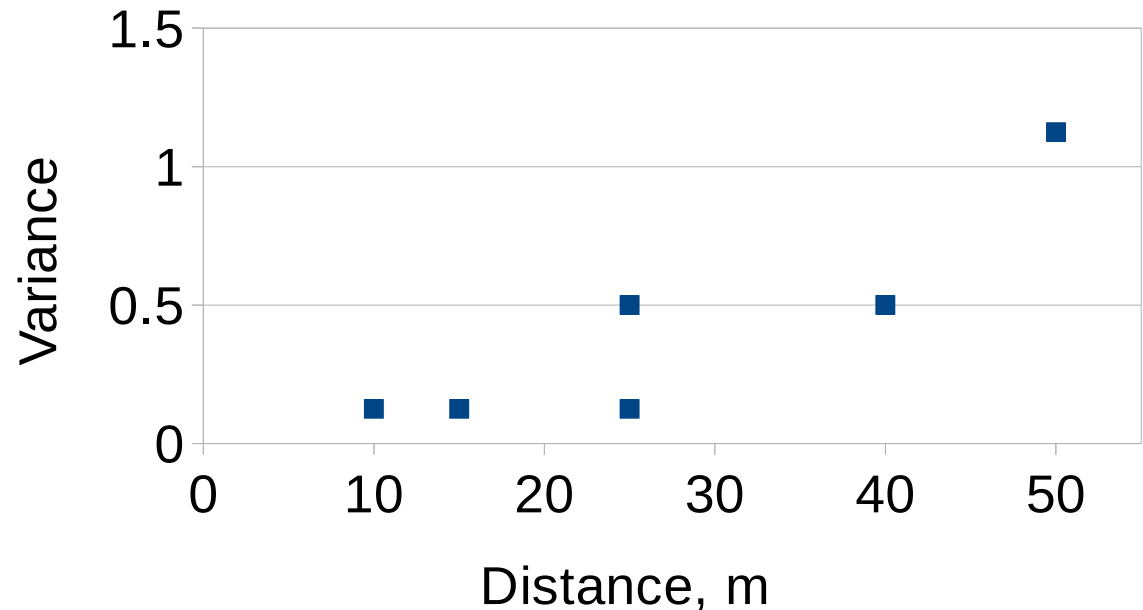
- Warning:
oversimplified!!!



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

Variogram

- Slightly more correct version

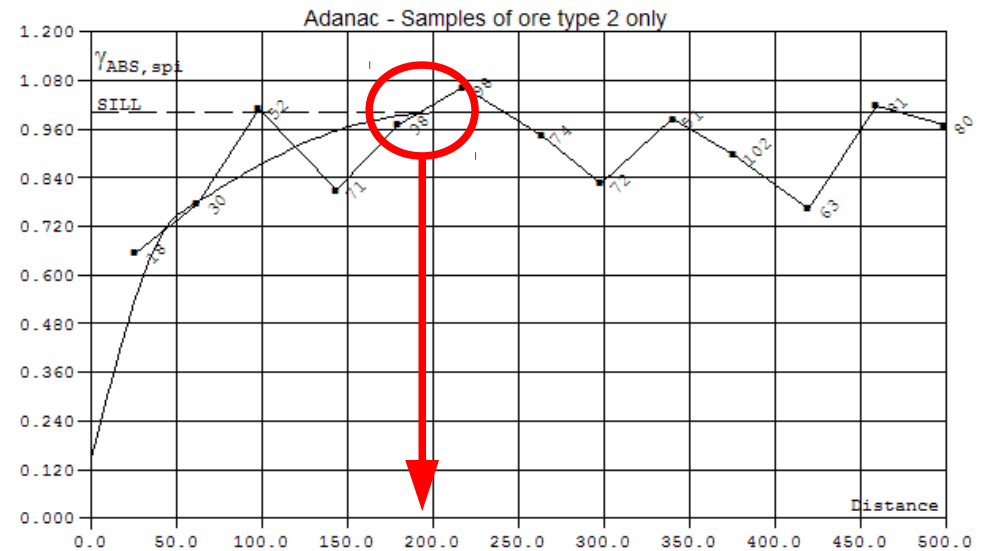


- Y-axis shows variance
- The population variance is shown as the “sill”

Variogram

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

– Bulled, CMP 2007



Variable : spi	Date : 18-11-2005
Variogram : Absolute	File : nspi2.gsd
Direction : avg	
Azimuth : 0.00	
Dip : -45.00	
Tolerance : 180.00	
Lag Dist : 40.00	
Gamma = N(0.1500) + S(0.4500, 50.0/50.0/50.0, 0.0/0.0/0.0) + S(0.4000, 200.0/200.0/200.0,	

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”

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 $A \times b$ 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

- 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 $\text{kW}\cdot\text{h}/\text{t}$ {alternative notation: $\text{kW}/(\text{t}/\text{h})$ }
- Mill power models determine the amount of grinding power available
 - P given in kW
- Dividing P by E gives the circuit throughput
 - $t/h = \text{kW} \div (\text{kW}\cdot\text{h}/\text{t})$

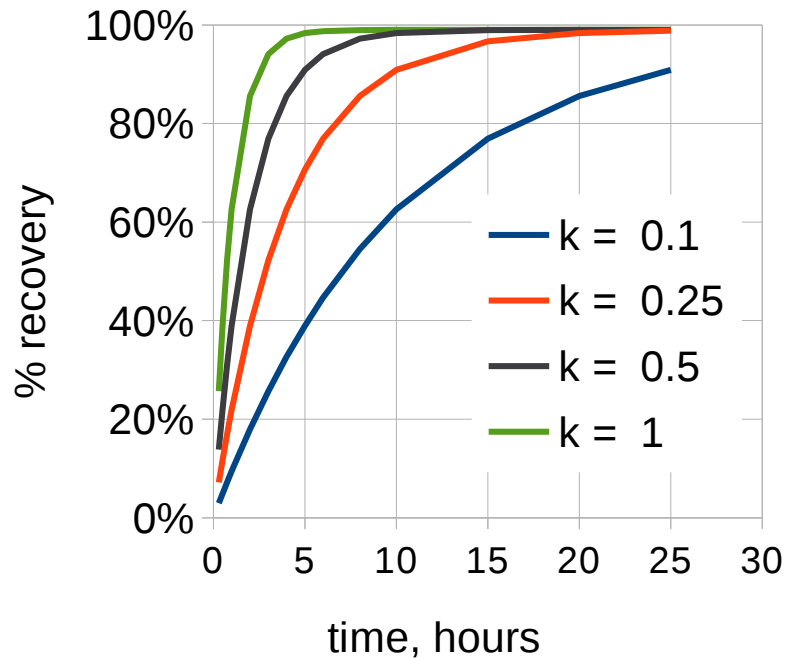
Throughput predictions

- 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 = $14,000 \text{ kW} \div 16.0 \text{ kW} = 875 \text{ t/h}$

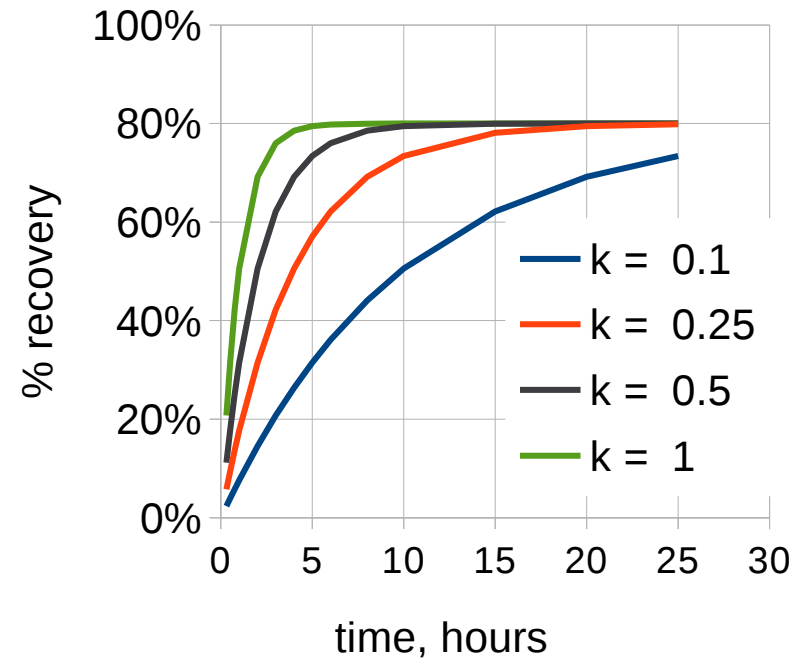
Recovery models

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

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) \times grade (g/t) \times 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, $\text{kWh/t} \times \text{t/h} \times \text{\$/kWh}$
 - include other operating costs
 - Processing time can be included as a cost penalty
 - revenue from 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.

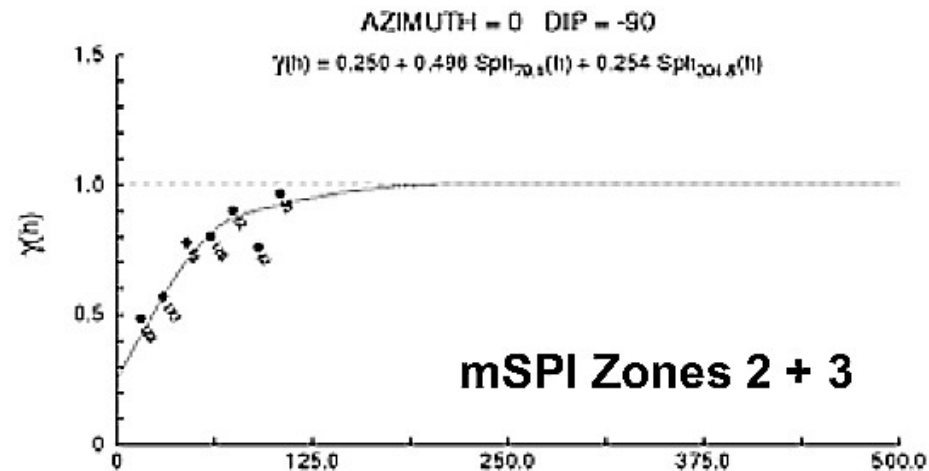
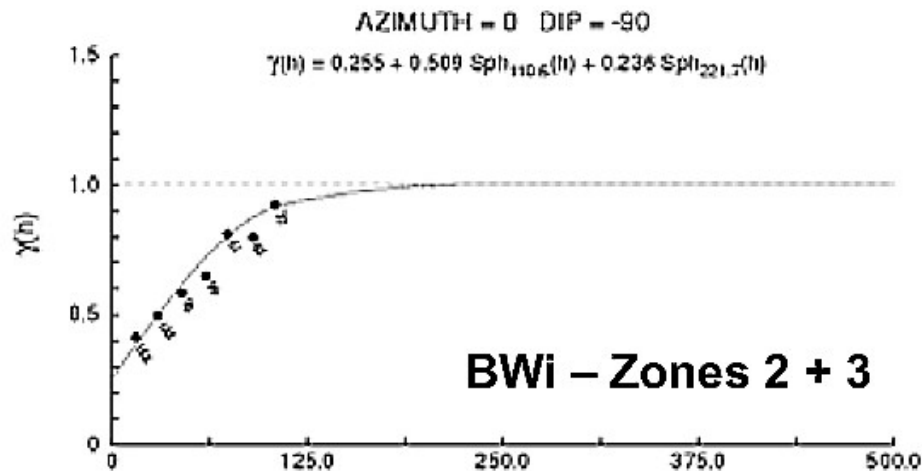
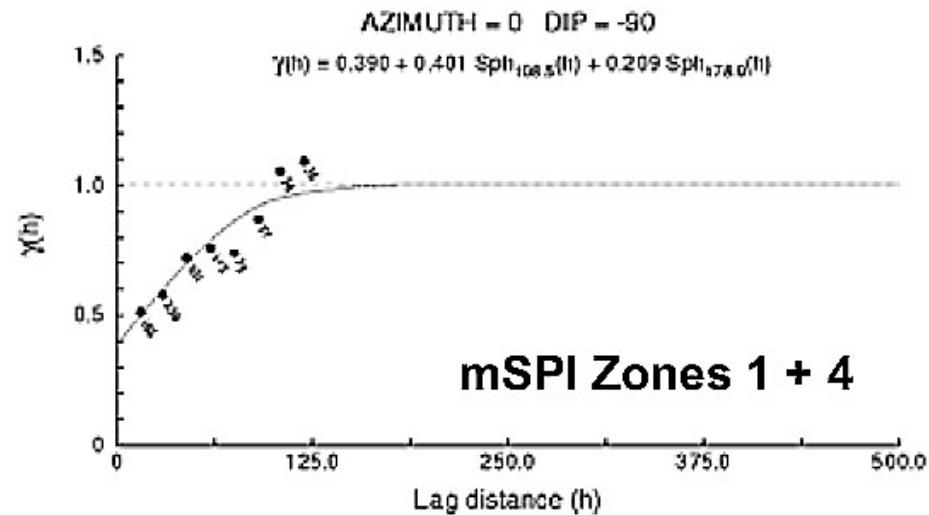
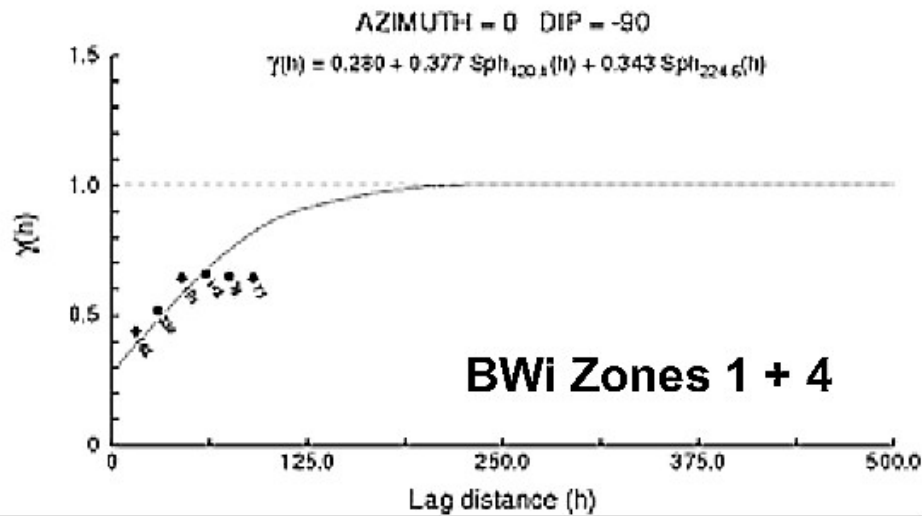
Examples of geometallurgy

- 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

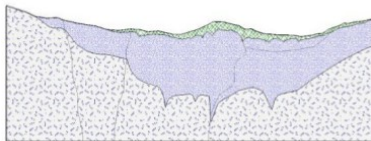
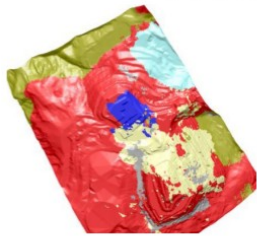
- Freeport-McMoRan study
 - Geometallurgical database used to compare SAG milling to HPGR in a detailed study.
- Andina, Piuquenes tailings (Chile)
 - Recovery and regrind energy for re-mining a tailings pond.

Escondida variograms



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.



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References

• References

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