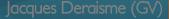


Localised Multivariate Uniform Conditioning: a BHP Billiton Iron Ore deposit applied case





Context



• Recoverable resource estimation:

- provide an estimation from wide-spaced data
- Tonnage and Metal quantities
- cut-offs are applied
- locally \rightarrow to selective mining units (SMU's).
- UC: an available geostatistical method
- Can be extended to multivariate settings using the potential correlations between the variables of economical interest
- Localisation of the results
- ightarrow Isatis is able to propose a possible flowchart







- Consider a SMU v, with grade Z(v)
- The recoverable resources at cut-off z are defined as:

- Ore:
$$T(z) = 1_{Z(v) \ge z}$$

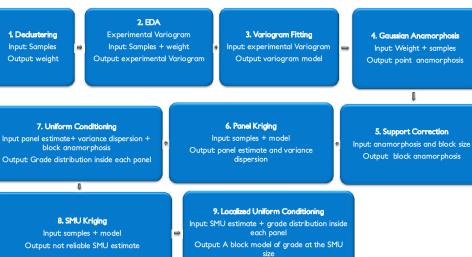
- Metal:
$$Q(z) = Z(v) \mathbf{1}_{Z(v) \ge z}$$

(to be multiplied by block tonnage = volume*density to be expressed in tons)



Isatis (possible) Workflow







4

The UC process



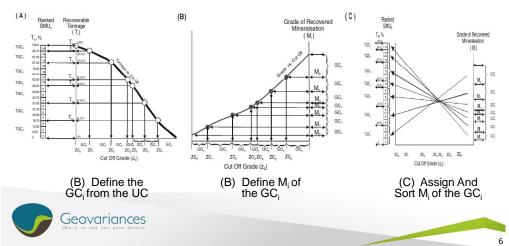
- Ordinary Kriging, storing kriged estimate and dispersion variance
- Point anamorphosis
 - An anamorphosis function converts the raw, non-Gaussian data (Z) to a variable (Y) having a Gaussian (normal) distribution
 - The distribution of punctual data is completely represented by the anamorphosis function
- Block anamorphosis (change of support)
 - The block anamorphosis determines the value of the coefficient r, which is used to determine the variance reduction of a particular support



The Localized UC Process



- The methodology has been proposed by Marat Abzalov (Rio Tinto),
 - see paper in Math. Geol.: the choice of the grades assigned to the blocks is guided by the local estimates of the block.



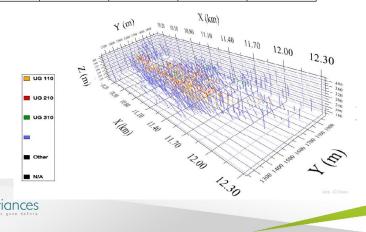
Data Overview



Data: 651inclined boreholes with 19172 3m composites split into 3

main ore domains.

UG	110	210	310	400
Count of composites	3631	1196	355	14530



7

Data Overview



5 grade elements are considered with different statistics in the

different domains

VARIABLE	Count	Minimum	Maximum	Mean	Std. Dev.	Variance
FE	19357	0.01	68.55	44.96	18.24	332.81
SIO2	19357	0.25	91.71	22.23	21.82	476.06
Р	19168	0.001	4.830	0.104	0.078	0.006
AL2O3	19357	0.05	44.28	4.68	5.89	34.74
LOI	19357	0.01	47.28	6.18	5.60	31.37



The Gaussian Anamorphosis



- Select several variables
- weights from declustering
- Interactive fitting
- Gaussian transformation: not necessary for recoverable resources
- Point Anamorphosis as parameter file
- The anamorphosis are made separately for each variable

Gaussian Anamorphosis Modeling	
Data Number of Variables: 🔽 👗 Load fro	m File
Input] Data / 3m_comp cores [Selection = sel UG[00001]] [8] Raw Variable #1 = FF [8] Raw Variable #2 = SIO2 [8] Raw Variable #3 = AL203 [8] Raw Variable #4 = P [8] Raw Variable #5 = LOI	
Weights [R] Weight Variable = None	• •
Output Formats Statistics	
Interactive Fitting Gaussian Transform Output Data / 3m comp cores [Selection - sel UG[00001]]	
Output Data / 3m_ comp cores [Selection - sel UG[00001]] [V] Gaussian for FE = 6 FE UG 110 [V] Gaussian for S102 = 6 S102 UG 110 [V] Gaussian for AL203 = 6 AL203 UG 110 [V] Gaussian for AL203 = 6 D UG 110	
Frequency Inversion =	
Point Anamorphosis Fe-SIO2-AL2O3-P-LOI UG 110 3m comp	
Print Tonnages Section 2.2 Create Graphic Windows for all Variables in Batch	
Run	Close



The Gaussian Anamorphosis



Gaussian anamorphosis without declustering is applied with 60 Hermite Polynomials

Example of Fe UG110



Change of Support



A change of support is applied on smus 5mx5mx3m.

Fe is then declared as the main variable

	FE	SIO2	AL2O3	Р	LOI
Punctual Variance (Anamorphosis)	11.47	9.62	1.46	0	2.92
Variogram Sill	10.85	8.56	1.45	0	2.98
Gamma(v,v)	5.42	4.65	0.64	0	1.02
Real Block Variance	6.05	4.97	0.81	0	1.91
Real Block Support Correction (r)	0.7813	0.819	0.7935	0.881	0.8128
Kriged Block Support Correction (s)	0.7813				
Kriged-Real Block Support Correction	1				
Main-Secondary Block Support					
Correction		-0.9034	-0.7632	-0.2444	-0.6183

Support Correction
Load Parameters from Block Anamorphosis
Input Data
Point Anamorphosis Fe-SIO2-AL2O3-P-LOI UG 110 3m comp
🗢 Univariate 🔶 Multivariate
Main Variable FE 🖃
Variogram Model FE-SI02-AL2O3-P-LOI UG 110
Support Definition
Define Block from Grid File
DX: V A 5 m NX: V A 5
DY: 🔻 🛦 📴 m NY: 💌 🛦 🗦
DZ: 👿 🔺 🛐 🛛 m NZ: 🔍 🔺 🏦
Rotation No rotation
 Block Discretization Block Partition
Normalize Variogram Sill (and Information Effect Variance-Covariance)
Information Effect (not computed)
Graphic Controls
Show: F Point Model F Block Model
Block Anamorphosis FE-SI02-AL203-P-LOI UG 110 block 5x5x3
Print Tonnages Output Formats
Run Calculate Close



Co-Kriging of the Panels



• $SMU = 5x5x3m^3$

 $Panels = 25x25x3m^3$

- Cokriging of panels achieved for each domain.
- All panels containing at least one block of a domain is kriged for that domain:
 - Mixed panels can then be kriged 2 or 3 times.



Co-Kriging of the Panels





Co-Kriging of the Panels



- UC Needs:
 - Estimated values;
 - Dispersion variance of the estimated value (Var Z*);
 - For all secondary variables, the covariance between the estimated value and the estimate of the main variable (Cov Z1*|Z*).



Standard (Co-)Kriging		
Calculation: Block		
Imput: Film Data / Am_comp cover [Sidertien = out UG00001] [M] rariable # = 7E 700 [M] variable # = 7E 700	0.0	
$\label{eq:constraints} \begin{split} \hline \hline Output Hear_{int} (or 11/20003) (Sectors - set 110) \\ \hline \hline Output Hear_{int} (or 11/20003) (Sectors - set 110) \\ \hline \hline Output Hear_{int} (or 11/20003) (Sectors - set 100) \\ \hline Output Hear_{int} (or 11/20033) (Sectors - set 100) \\ \hline Output Hear_{int} (or 11/20033) (Sectors - set 100) \\ \hline Output Hear_{int} (or 11/20033) (Sectors - set 100) \\ \hline Output Hear_{int} (or 11/20033) (Sectors - set 100) \\ \hline Output Hear_{int} (or 11/20033) (Sectors - set 100) \\ \hline Output Hear_{int} (or 11/20033) (Sectors - set 100)$	N N	
Kriging Parameters		
Model FE-S102-ALZ03-P-L01UG 110	Edit	
Epecial Model Options No special model option	Edit	
Local Parameters No local parameters Special Kriging Options No special kriging option		
Run Test	Cluse	

Uniform Conditioning



	IO2-AL2O3-P-LOI UG 110 block 5x5x3	Print
 Taun, "Eriged Yuhas R "Bain" Bayersian V R "Sec1" Kriged Yahas Sec1" Kriged Yahas R "Sec2" Respective R "Sec2" Respective R "Sec2" Respective R "Sec2" Respective R "Sec2" Respective R "Sec2" Respective R "Sec3" Respective R "Sec4" Respective R Sec4" R Sec4" Respective R Sec4" R Sec4	ariance = Var 2.2 FF U0 10 = Cok S102 U0 110 ariance. Var 2.2 = Cok S102 U0 110 ariance. Var 2.2 = Cok AL203 U0 110 ariance = Var 2.2 AL203 U0 110 ariance = Var 2.2 AL203 U0 110 ariance = Var 2.4 C.203 U0 110 ariance = Var 2.4 C.203 U0 110 ariance = Var 2.4 F U0 110 = Cok III 00 110	
Nain Variable Cutoffs Definition Number of Iso-frequency Class		
Variances Format Decin		F H
Variances Format Decin	FE (Block)	



Localisation of the results



- For Localized Uniform Conditioning Post-Processing, Fe grade of blocks 5mx5mx3m³ cokriged.
- Blocks of different domains cokriged in turn with the variogram parameters of the domain they belong to.

tandard (Co-)	Kriging	
Calculation:	Block =	
Number of Varia	ables: 💌 🔺 🔰 📃 Full Set of Output Varia	bles
vlaximum Numk	er of External Drifts: 💌 🛦 🗓	
Input File [Data / 3m_comp cores [Selection = sel UG{UG=110}]	. 🖂 🖪
[R] Variab	le #1 = FE	
[R] Variab	le #2 = SIO2 le #3 = AL203	
[R] Variab	le #4 = P	
	le #5 = LOI	
	ce of Measurement error = None g Weights - None	5
Output File	Grid / 5x5x3 [Selection = sel 110]	
	tion for FE - Cok Fe	
	for FE = None tion for SIO2 = None	
W St dev	for SI02 = None	
	tion for AL203 = None for AL203 = None	
[V] Estima	tion for P = None	
[W] St dev	for P - None	<u>N</u>
Kriging Parame	ters	
Model FE-:	SIO2-AL2O3-P-LOI UG 110	Edit
Special Model	Options No special model option	
Neighborhood.	moving	Edit
Local Paramete	ers No local parameters	
Special Kriging	Options No special kriging option	
Run 1	Test	Close

Localisation of the results

- Local option: for each individual domain. Q assigned to the blocks of the same domain.
 - The condition: apply on the block file a selection for the blocks of that domain and to transform the tonnage and metals of the panel file by the proportion of the blocks of that domain.
- **Global option**: one Uniform Conditioning of each domain and combine the tonnages and metals by weighting by the proportions of each domain.
 - Then the Localized Uniform Conditioning is run once. In that case there is no guarantee that the grade assigned to one block comes from the grade tonnage curve of the same domain.



Localized MUC



Local option: then the Localized Uniform Conditioning is achieved with the selection on the blocks file of the same domain activated

<pre>in Marco Variable Metal 0 = UC TR (Proced) in Marco Variable Metal 0 11 = ProcE102 ([Nexced] seendary Marco Variable Metal 0 12 = UC.AL203 ([Nexced] seendary Marco Variable Metal 0 12 = UC.AL203 ([Nexced] seendary Marco Variable Metal 0 14 = UC.DL0 ([Nexced] seendary Marco Variable Metal 0 14 = UC.DL0 ([Nexced] seendary Marco Variable Metal 0 14 = UC.DL0 ([Nexced] seendary Marco Variable Metal 0 14 = UC.DL0 ([Nexced] seendary Marco Variable Metal 0 14 = UC.DL0 ([Nexced] seendary Marco Variable Metal 0 14 = UC.DL0 ([Nexced] seendary Marco Variable Nexced = Sok Fe U.G. for Main Variable Stade = Sok Fe U.G. for Main Variable Stade = 1000 FIGE local option U.G. for Secondary Variable #1 = LNU0 FIGE local option U.G. for Secondary Variable #1 = LNU0 F local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #4 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option U.G. for Secondary Variable #1 = LNU0 FL LOI local option </pre>	Panel Grid File	Grid / 25x25x3 [Selection = sel 110]
riged Main Variable Grade = Cok Fe .U.C. for Main Variable = LMUC FE local option .U.O. for Secondary Variable #1 - LMUC 5102 local option .U.C. for Secondary Variable #2 = LMUC AL203 local optio .U.C. for Secondary Variable #2 = LMUC Plocal option	[R] Secondary [R] Secondary [R] Secondary [R] Secondary	<pre>Macro Variable Metal 0 #1 = UC_SI02_0[xxxxx] Macro Variable Metal 0 #2 = UC_AL203_0[xxxxx] Macro Variable Metal 0 #3 = UC_P_0[xxxxx] Macro Variable Metal 0 #4 = UC L01 0[xxxxx]</pre>
C	[R] Kriged M [W] L.U.C. f [W] L.U.C. f [W] L.U.C. f [W] L.U.C. f [W] L.U.C. f	in Variable Grade = Cok Fe r Main Variable = LMUC FE local option r Secondary Variable #1 = LMUC 5102 local option rr Secondary Variable #2 = LMUC AL203 local option r Secondary Variable #3 = LMUC P local option

UC post-processing



Global option: Then LUC applied once to assign the grades to the blocks (possibly belonging to different domains) inside the panels.

		Grid / 25x25x3 [Selection = None] o Variable Metal Q = UC FE Q[xxxxx]	
[R]	Secondary	o Variable Metal Q = UC_FL_Q[xxxxx] Nacro Variable Metal Q #1 = UC_SIO2_Q[xxxxx] Nacro Variable Metal Q #2 = UC_AL2O3_Q[xxxxx]	
[R]	Secondary	Macro Variable Metal Q #3 = UC_P_Q[xxxxx]	
[R] [V]	Secondary Skipped P	Macro Variable Metal Q #4 = UC_LOI_Q[xxxxx] anels Selection (optional) = sel skipped panels globa	1
			1
Block	Grid File	Grid / 5x5x3 [Selection = sel 110 or 210]	Defa
[R]	Kriged Ma	in Variable Grade = Cok Fe r Main Variable = LMUC FE global option	
[11]	L.U.C. fo	r Secondary Variable #1 = LMUC SIO2 global option	
[10]	L.U.C. fo	r Secondary Variable #2 = LNUC AL203 global option r Secondary Variable #3 = LNUC P global option	
i wj	L.U.C. fo	r Secondary Variable #4 = LNUC LOI global option	





Results & Conclusions



Results & Conclusions



The block model obtained by LMUC shows higher dispersion than the direct block cokriging.





The block model obtained by LMUC shows higher dispersion than the direct block cokriging.





Warning: Discretisation of the cut-off is a critical parameter of the UC/LMUC quality



22 cut-offs between 50 & 70%

41 cut-offs between 50 & 70%



The grade tonnage curves obtained from UC and from LMUC grades are the same, with little difference between local and global LUC methods.



Results & Conclusions



The correlations between all variables, including the second variables correctly reproduced (In parenthesis the coefficient of correlation of 3m composites).

VARIABLE	LMUC FE	LMUC SIO2	LMUC P	LMUC AL2O3	LMUC LOI
LMUC FE	1.00	-0.86	-0.28	-0.83	-0.67
LINUC FE		(-0.84)	(-0.27)	(-0.85)	(-0.66)
LMUC SIO2	-0.86	1.00	0.08	0.54	0.31
LINUC SIUZ	(-0.84)		(-0.03)	(0.58)	(0.26)
LMUC P	-0.28	0.08	1.00	0.27	0.45
LINCE	(-0.27)	(0.03)		(0.25)	(0.5)
LMUC AL2O3	-0.83	0.54	0.27	1.00	30 0.57 🐇
LINUC ALZUS	(-0.85)	(0.58)	(0.25)		(0.56)
LMUC LOI	-0.67	0.31	0.45	0.57 ฐ	1.00
	(-0.66)	(0.26)	(0.5)	(0.56)	20 -
				loca	
				8102	4
				2 MUC 8	10 -
				ħ	
Consider					0 -

LMUC FE local option