Simulation of Grade Control, Stockpiling and Stacking for Compliance Testing of Blending Strategies

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Conditional simulation is typically used for quantifying uncertainty in a resource or reserve. Realizations are not often carried past this stage due to a lack of tools for processing multiple realizations in pit optimization or economic software. This paper shows one application. A simulated realization was used to assess the uncertainty in the furnace feed for a nickel laterite deposit. Different scenarios for grade control, stockpiling, and stacking/reclaiming were considered to quantify their importance and impact on the variability of the furnace feed.

Introduction

This paper is the result of a project proposed by Anglo American. The objective of the project was to evaluate the variability of ore being fed to the furnace with alternate grade control, stockpiling and blending/stacking strategies. Base case scenarios for grade control, stockpiling, and stacking had already been chosen. Anglo American wanted verification of the base case that they had chosen by evaluating different options. Three different grade control schemes, three different stockpiling options, and four different stacking options had to be considered. Nearly 40 potential cases were evaluated.

The mining process starts by collecting close spaced grade control samples. No blasting is required in the ore. This allows the grade control samples to be collected throughout the entire thickness of the deposit. The grade control drilling is used to create a grade control model with kriging. The deposit is classified according to the grade control model. The material in the deposit is mined as either ore, or waste depending on the grade control model. The mined material is sent to stockpiles for storage and preliminary blending. The material in the stockpiles is then reclaimed and sent to a large stacker for final blending before being sent to the furnace. It is critical that the furnace feed meet the requirements set out during the design of the furnace.

The project was broken down into the following steps: (1) building a reference model, (2) stockpiling the ore and waste material, (3) reclaiming the stockpiles and blending the material for feed to a large stacker, and (4) a sensitivity analysis. Each point mentioned above will be discussed below.

Deposit Characteristics and Feed Requirements

There are three classifications for material in the deposit; acidic ore, basic ore, and waste. Waste is any material that has a nickel grade that is less than 0.9%. This could be internal waste or low grade areas. Acidic ore is material that has a nickel grade greater than 0.9% and an SMR greater than 2.5. Basic ore has a nickel grade greater than 0.9% and an SMR less than 2.5. SMR stands for the silica (SiO_2) to magnesium (MgO) ratio. It is an important ratio for the furnace.

The deposit is divided into two main regions by a north-south line. There has been some geologically activity in the east resulting in some complex structures, while the ore in the western region is relatively flat lying. WTO and ETO are used to define the west type ore and east type ore respectively.

The furnace requirements are very specific. They were provided by Anglo American. The feed should have a silica magnesium ratio (SMR) as close to 1.75 as possible. The SMR is the critical parameter for the furnace feed. Keeping the SMR at the target value allows the furnace to run in a self-sustaining state. If the SMR gets too low, too much energy will be required to run the furnace. If it gets too high, the reaction inside the furnace will produce too much heat and will cause damage to the furnace. The other controlling parameter is the iron content in the feed. There is no real control on the iron feed, except that it can not exceed 18.5%. The following table lists the furnace feed requirements,

Parameter	**Target**	**Lower Limit**	**Upper Limit**	**Lower Limit (%)**	**Upper Limit (%)**	
SiO_2:MgO Ratio	1.75	1.66	1.79	-5.0%	+2.0%	0.02
SiO_2		35	45	-5.0%	+4.0%	1.5
MgO		20	25	-6.0%	+10.0%	1.4
Fe		9.7	18.5	-15.0%	+10.0%	1.7

Reference Model

The geostatistical modeling led to a high resolution realization at the resolution of ½ of a truck load (15 to 20 tonne blocks), that is, a 2.5m by 2.5m by 2.5 m cell size (about 27 million cells). The original topography and drillhole data are show in Figure 1. There were 30,204 assays in the drillhole data.

Four rock types were used for creating the reference model. They are a combination of the acidic and basic ore types and the east and west areas.

RT	Description	ORE	EW
15	Basic ETO	200	5 (ETO)
16	Basic WTO	200	6 (WTO)
25	Acid ETO	250/275/300	5 (ETO)
26	Acid WTO	250/275/300	6 (WTO)

Preliminary Statistics

Figures 2 through 5 show the histograms of the grades by rock type. The histograms are reasonably well behaved. A table of the summary statistics is given below:

RT	N	Ni		Fe		SiO2		MgO	
		m		m		m		m	
15	6323	1.73	0.76	12.58	8.32	36.83	7.28	27.60	8.98
16	4639	1.81	0.81	12.94	7.40	39.36	8.08	24.71	8.99
25	771	1.53	0.70	27.19	13.05	31.30	15.55	10.56	10.68
26	6457	1.66	0.95	23.66	11.18	39.59	16.24	8.37	8.08

Note that the acid and basic ores are quite different. The nickel and SiO2 grades are lower in the acid rock types, but not dramatically. The Fe grades are significantly higher in the acid rock type and the MgO grade is significantly less. These have a large affect on blending.

Scatterplots between all variables are shown on Figures 6 through 9. Although different in some details, all rock types show similar features. The relationship of the different variables to Ni is weak. The SiO2/MgO cross plot is characterized by low SiO2 and low MgO, high SiO2 and low MgO, and median SiO2 and high MgO. These relationships will be captured in the stepwise transform described below. The correlation coefficients are not particularly informative, but they are tabulated below for interest and to judge the stability of the statistics:

RT	Ni-Fe	Ni-SiO2	Ni-MgO	Fe-SiO2	Fe-MgO	SiO2-MgO
15	0.407	-0.292	-0.397	-0.619	-0.869	0.343
16	0.331	-0.146	-0.301	-0.379	-0.809	-0.056
25	0.087	-0.178	0.194	-0.867	-0.831	0.525
26	-0.046	-0.127	0.495	-0.767	-0.595	0.116

Stepwise Transformation of Grades

The grades are transformed in a stepwise manner so that the final multivariate structure is preserved as closely as possible. There are many non-linear, constraint and heteroscedastic features on the cross plots (6 to 9). The following order was chosen:

1. Ni — Nickel is the metal of interest, but poorly correlated with the rest
2. Fe | Ni — Iron becomes less variable with high nickel grade
3. SiO2 | Fe — Silica is strongly related to iron
4. MgO | Fe — Magnesia is highly correlated to iron

It is possible to correlate a variable to two secondary variables; however, that requires more data. The relationships not explicitly accounted for (MgO to SiO2 and MgO, SiO2 to Ni,…) will be captured by the relationships that are explicitly accounted for. Variography is considered with the normal scores transforms and the stepwise conditional transforms.

The final transformation was arrived at after experimenting with MgO|SiO2 (instead of MgO|Fe), but the overall relationships were not reproduced as well. There are a small percentage of the samples with high MgO and SiO2.

Simulation

SGS of the stepwise transformed variables was performed. The simulation is straightforward: no transformation is performed explicitly – it is handled by the stepwise transformation, no trends are used – that could be considered in the future, 16 previously simulated grid nodes is considered adequate.

The following seven steps summarize how the simulation and back transformation proceeds:

1. Stepwise transform of Ni (variable one) and Fe (variable two).
2. Stepwise transform of Fe (variable one – left untransformed) and SiO2

3. Stepwise transform of Fe (variable one – left untransformed) and MgO
4. Gaussian simulation of Ni and Fe (from step one), SiO_2 (from step 2) and MgO (from step 3).
5. Reverse stepwise transformation of Ni and Fe together.
6. Reverse stepwise transformation of SiO_2 given Fe (from step 5).
7. Reverse stepwise transformation of MgO given Fe (from step 5).

The variograms in the principal directions were calculated with the gridded normal scores realization. The normal scores variograms were reproduced within reasonable statistical fluctuations. Note that the statistics above and the variograms were checked with only the grid cells that were informed by the rock type model.

The cross plots between all variables also should be reproduced within reasonable statistical fluctuations after back transformation. The normal scores values, of course, are uncorrelated. Figures 10 to 13 show the cross plot reproduction. There is a slight change in statistics due to declustering; however, the cross plots are reproduced very closely.

Formatting for Subsequent Calculations

The four grade realizations were written out with the pushback number, the pit number, the bench elevation, the X block index, the Y block index. The pushback number was provided by Anglo American from one of their preliminary pit designs. The pushbacks will be used for the mining simulator in one of the subsequent steps. Only blocks that have been informed are written to the output file. This format can be considered in the grade control module and the mining simulation.

Grade Control

Grade control includes collecting samples and then estimating block grades. The general procedure is: (1) simulate grade control drilling from the reference model at a spacing that may be implemented in the mine, (2) assign a sampling error to the drilling results, and (3) estimate the block grades that will be used for selection during mining.

Three grade control schemes were considered: (1) a base case, (2) a high selectivity, or closely spaced, case, and (3) a low selectivity, or widely spaced, case:

	ETO	**WTO**
Base Case	12.5 m by 12.5m	12.5 m by 6.25 m
High Selectivity	6.25 m by 6.25 m	6.25m by 6.25 m
Low Selectivity	25.0 m by 25.0 m	25.0 m by 12.5 m

Simulated Grade Control Sampling

The grade control samples were extracted on a regular grid with a sampling error. The spacing of the grade control drilling is potentially different in ETO and WTO areas. A close up of the samples for the base case are shown in Figure 14. Figure 15 and Figure 16 show the samples taken for the high and low selectivity cases respectively.

The relative sampling error was normally distributed with a standard deviation of 5%, that is:

$$Z_{\text{grade control}} = (1 + y \cdot 0.05) \cdot Z_{\text{reference}}$$

where y is a standard normal deviate. This resulted in some samples have almost no sampling error, and some samples having a relatively high error (greater than 10%). There was no systematic bias applied to the grade control samples.

Grade Control Estimation

Nickel, iron, silica, and magnesia were sampled by the grade control drilling. Each variable was kriged by rock type using ordinary kriging. The correlation between the variables need not be accounted for explicitly because they are equally sampled (all variables available at all data locations) and closely samples.

Experimental variograms were calculated for the sampled data. The experimental variograms were similar to the normal score variograms used for generating the simulated model, but with a modestly higher nugget effect due to the sampling errors. Therefore, the normal score variograms were also used for kriging the grade control model.

The simulated nickel model and the three grade control models are shown in Figure 17. The areas of low and high nickel are reproduced in the base case grade control model. The high and low areas are reproduced better in the high selectivity grade control model than the base case model. The low selectivity model does not reproduce the high and low areas very well.

Mining and Stockpiling

The stockpiling was done using the reference grade realization and the grade control models. The goal is to simulate mining the deposit to stockpiles, according to the grade control model. The reference grade values and the grade control grades will be carried forward to the stacking and reclaiming process. Three cases were considered for the mining and stockpiling: (1) base case stockpiles of 25000 tonnes, (2) larger stockpiles for the wet season of 50000 tonnes, and (3) stockpiles that were constructed at random.

Mining Simulation

There will be two backhoes mining ore in as many as six pits / mine faces. 35.7 tonne trucks will be used for mining. The moisture content of the ore will be about 30% from the mine prior to drying. Average densities were used. The dry density for acid type ore used was 0.97 and for basic ore was 1.18. The stockpiles are built by dumping truckloads 3m apart along the full 150 m length (50 truck loads). All 50 truckloads are aimed at the same characteristics. The material is dozed up the pile after two rows have been dumped.

The deposit was mined in a sequential fashion: by-pushback and by-pit. Pushback 1 was mined before pushback 2, and pit 1 in pushback 1 was mined before pit 2 in pushback 1. Pushback 5 was not mined for this study – this is the poorly defined material to be delineated over the early years of the mine. Within each pit, the deposit was mined from top to bottom by mining the top bench first, then moving one bench down. The benches followed elevation and not the surface.

Two adjacent blocks were loaded into a truck and each truckload was classified based on the grade control estimates. The reference values and grade control values were tracked to the stockpile. Estimated and true grades were carried through all subsequent calculations.

Stockpiling

Stockpiles are constructed for the wet season; when mining stops for three months. The stockpiles for the dry season are likely to be smaller. The simulation study assumed that all material will be rehandled, that is, stockpiled and then reclaimed and hauled to the plant. The wet-season stockpiles are constructed according to the following parameters: height of 8.7 m, length of 150 m, width of 57 m, back slope of 34 degrees, front slope of 11 degrees. There is a 50,000 wet tonne capacity (30% moisture). It is expected that there will be 12 seasonal stockpiles.

The base case scenario will be for the dry season. The stockpiles are a smaller 25,000 wet tonnes, although they are the same 150 m length – the height will be reduced. The target will be for 5 to 10 stockpiles. The first option considered will be for bigger piles – the same as the wet season. The second option will be for a random order – close to mining directly to the stacker.

Each truckload was classified as high SMR or low SMR based on the grade control estimates. The low SMR ore was sent to one stockpile and the high SMR ore was sent to another stockpile. One high SMR stockpile and one low SMR stockpile were built at a time. Material that had an estimated SMR $\le$ 1.75 was sent to a low SMR stockpile. Material with an estimate SMR > 1.75 was sent to a high SMR stockpile.

An additional case was considered where two different types of high SMR stockpiles were constructed: (1) a high SMR pile with a low, <1.5%, Ni grade and (2) a high SMR pile with a high, >1.5%, Ni grade. The low Ni stockpiles were kept in reserve if the high Ni, high SMR stockpiles were exhausted.

Stacking and Reclaiming

The stockpiles from the previous step are mined and fed to the stacker to build its large stacker pile. The stacker pile is then reclaimed and fed to the furnace. Four scenarios were considered: (1) base case stacker piles that contained 100000 tonnes, (2) small stacker piles that contained 50000 tonnes, (3) large stacker piles that contained 200000 tonnes, and (4) base case stacker piles with a 3-day lag to get the sample assays back.

The feed to the stacker was a combination from the low SMR and high SMR stockpiles. The estimated SiO_2 and MgO content of each pile was used to calculate the initial blend from the stockpiles. While the stacker pile was being built, samples were taken at 2 hour intervals. An error of 5% was added to these samples. The assayed samples were used to adjust the blend from the stockpiles to ensure the stacker pile met the target SMR of 1.75. The stacker pile was then reclaimed and fed to the furnace. The variability of the feed to the furnace was used to judge how good each scenario performed. Figure 18 shows the furnace feed for the base case.

The stacker algorithm was designed to ensure that the stacker pile meets the furnace requirements. If the pile does not meet the specified SMR, from the sampling, then the blend is adjusted so that the pile will have an SMR of 1.75 within a day. The targeting algorithm is:

$$tr = \frac{1.75 \cdot \left(t_p + t_a\right) - actsmr \cdot t_p}{t_a}$$

Where *tr* is the target SMR of the material to add to the pile, *actsmr* is the actual SMR of the material in the pile, t_p is the tones on the pile, and t_a is the tones to add to the pile. This corrected an out of specification stacker pile within a day.

Sensitivity Analysis

A sensitivity analysis was done to assess the impact that each variable had on the furnace feed. The standard deviation of the furnace feed SMR was used to compare the 36 different possible scenarios. The lower the standard deviation, the better that scenario was rated.

Recall the different scenarios to consider. There were three grade control schemes were considered: (1) a base case grade control program, (2) a high selective, or closely spaced, case, and (3) a low selectivity, or widely spaced, case. There were three different mining and stockpiling cases: (1) base case stockpiles, (2) larger stockpiles for the wet season, and (3) stockpiles that were constructed at random. Finally, there were four scenarios for the stacking and reclaiming: (1) base case stacker piles, (2) small stacker piles, (3) large stacker piles, and (4) base case stacker piles with a 3-day lag to get the sample assays back. In summary:

Variable	Cases	Description
Grade Control	3	Base case, close spaced, wide spaced
Stockpiles	3	Base case, wet season, random
Stacker	4	Base case, half length, double length, and three day lag

We considered the full set of 3x3x4=36 cases, which is the full combinatorial of scenarios.

Figure 19 shows two different histograms. The histogram on the left is for the low selectivity sampling case and the histogram on the right is for the base sampling case. There is an obvious reduction in variability (improvement in blending) with the denser base case sampling.

Figure 20 shows the results of the sensitivity analysis. It is clear from the results that the most important factor is grade control for reducing the SMR variability. Closer grade control samples resulted in better estimates of SiO2 and MgO, and therefore a more stable feed to the furnace. The second most important factor was the stockpiling method. The base case and wet season stockpiles showed no difference in their affect on the SMR of the furnace feed. The random stockpiling showed a large improvement over the base case stockpiles for the base case sampling. Even though the random stockpiling method showed an improvement over the other methods, it is not a feasible operating alternative. It is important to note that the random scheme is not the same as sending the material from the mine to the stacker; it just means that the stockpiles are built with maximum homogeneity – rather than targeting SMR and Ni in their construction. The least important factor was the stacker pile size and sample delay.

Figure 21 shows the furnace feed that would be achieved with the low selectivity samples and base case stockpiling and stacking. Figure 22 shows the furnace feed with the base case samples. And Figure 23 shows the furnace feed with the high selectivity samples. Note that the variability of the SMR in the furnace feed decreases as the grade control sampling is done on a smaller grid. There is a large reduction in variability from the low selectivity case to the base case, but not a very large drop from the base case to the high selectivity case. Recall the plant requirements listed earlier. They are in the following table:

Parameter	**Target**	**Lower Limit**	**Upper Limit**	**Lower Limit (%)**	**Upper Limit (%)**	
SiO_2:MgO	1.75	1.66	1.79	-5.0%	+2.0%	0.02
SiO_2		35	45	-5.0%	+4.0%	1.5
MgO		20	25	-6.0%	+10.0%	1.4
Fe		9.7	18.5	-15.0%	+10.0%	1.7

If we calculate the statistics for the base case scenario, we get the following numbers:

Parameter	**Average**	**Lower Limit**	**Upper Limit**	
SiO_2:MgO Ratio	1.752	1.729	1.765	0.006
SiO_2	38.36	36.26	39.79	0.64
MgO	21.90	20.71	22.68	0.36
Fe	15.31	14.00	17.60	0.54

Note that all of the requirements have been met. In other words, the base case scenario can achieve the required plant feed. However, choosing which scenarios to use may require additional work. One interesting point that came out of the sensitivity study was the effect that the grade control had on the nickel coming out of the furnace.

Effect of Grade Control on Nickel Selectivity

An interesting result came out of the sensitivity study. That is a more intensive grade control program has two advantages: (1) the SMR variability of the plant feed can be reduced, and (2) the average nickel grade of the processed ore increases. The table below shows the increase in Nickel grade for the different grade control scenarios. The nickel grade in table is calculated from the plant feed, not the insitu ore.

Grade Control Drilling	Average % Ni	Average % Ni Blending for Ni
Low Selectivity	1.604	1.737
Base	1.633	1.774
High Selectivity	1.665	1.821

Figure 24 shows how the selectivity of the mine improves with more grade control drilling. The actual Ni above a cutoff of 0.9 does not change. The estimated nickel grade above the cutoff does not change either. What changes is the classification of the material above cutoff. The mined nickel grade increases from 1.58 for the coarse grade control drilling to 1.62 for the base case drilling and to 1.65 %Ni for the fine spaced grade control drilling.

Conclusions

This study has shown that conditional simulation is a powerful tool for uncertainty assessment at any point in the mining process. It is a powerful, yet simple tool, for quantifying uncertainty in complex settings.

The difficulty needs to be faced is processing multiple realizations. It is time consuming and tedious for someone to repeat the same task 50-100 times with different realizations. Post-processing tools need to be developed to take full advantage of simulation.

Acknowledgments

The authors would like to thank Anglo American for commissioning the initial project and for allowing us to present the results.

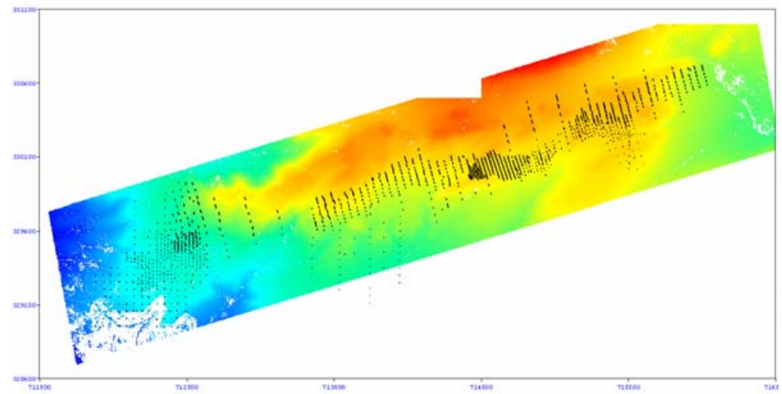

Figure 1: Map of the original topography and drillhole data.

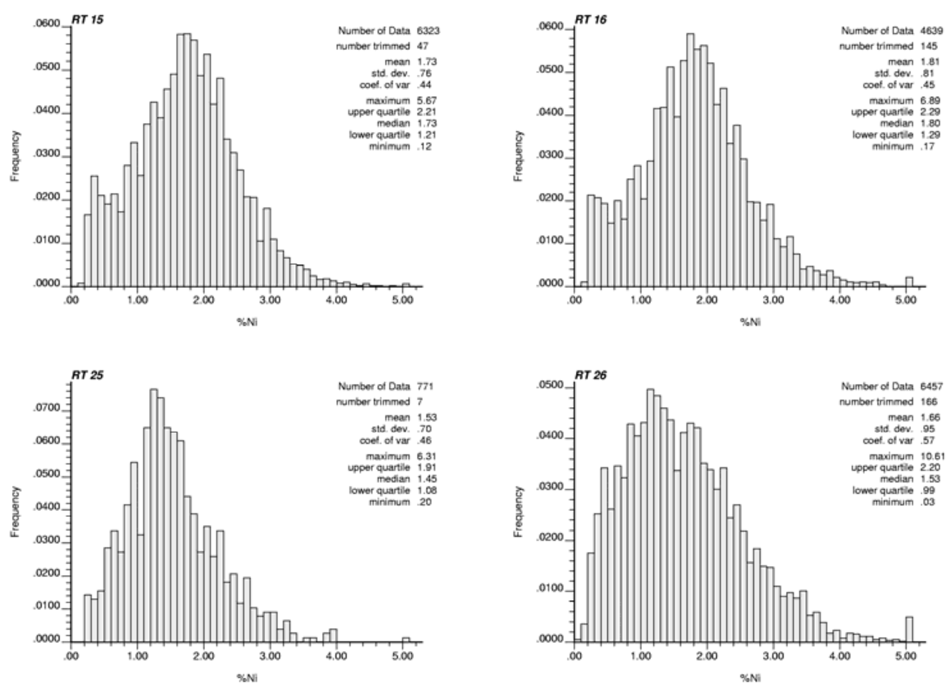

Figure 2: Histograms of Ni grade by modeling rock type.

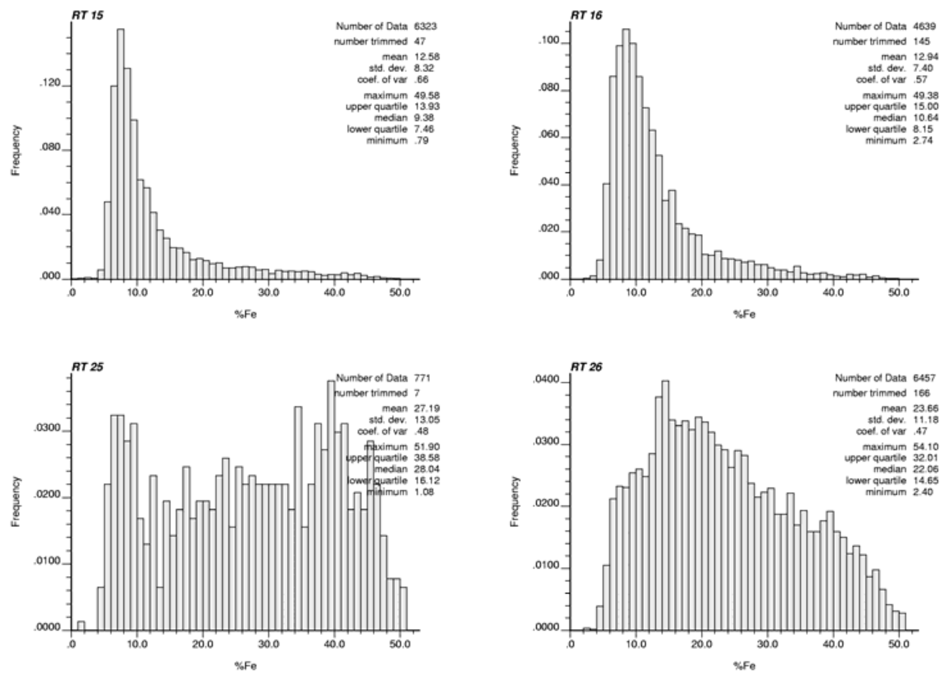

Figure 3: Histograms of Fe grade by modeling rock type.

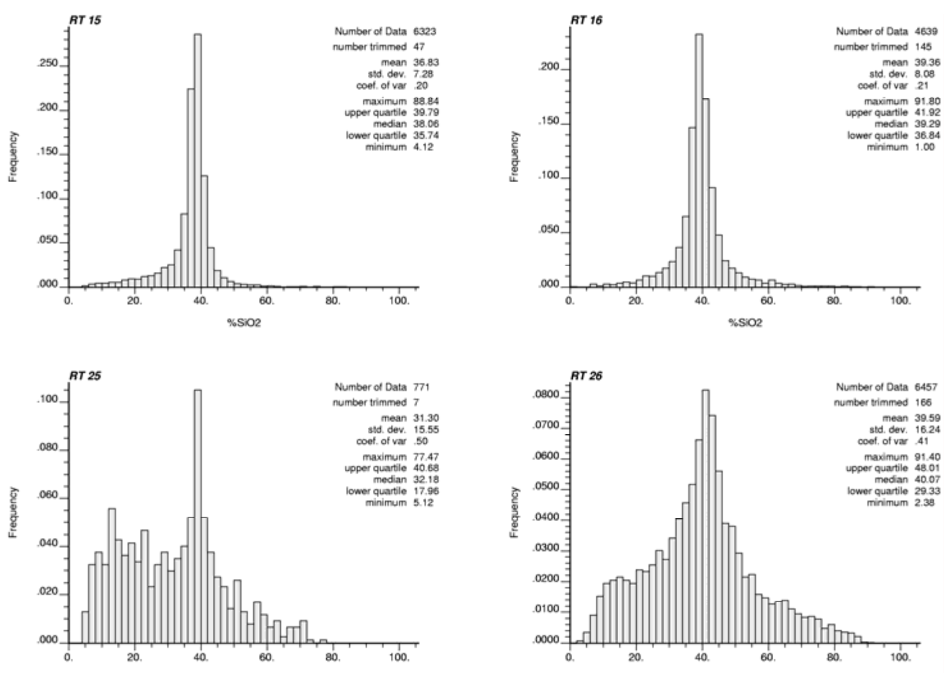

Figure 4: Histograms of SiO_2 grade by modeling rock type.

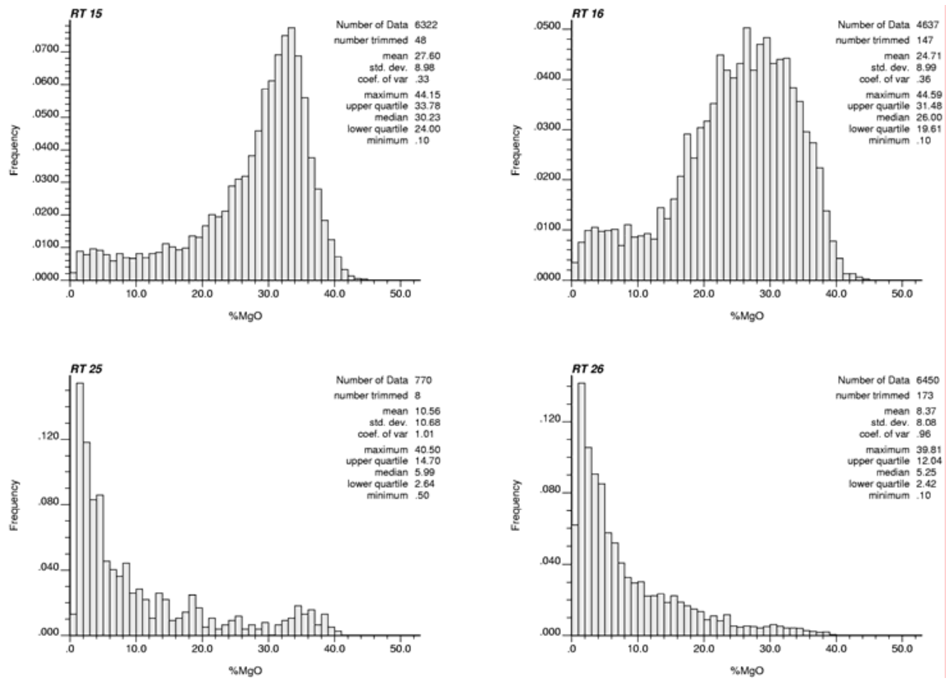

Figure 5: Histograms of MgO grade by modeling rock type.

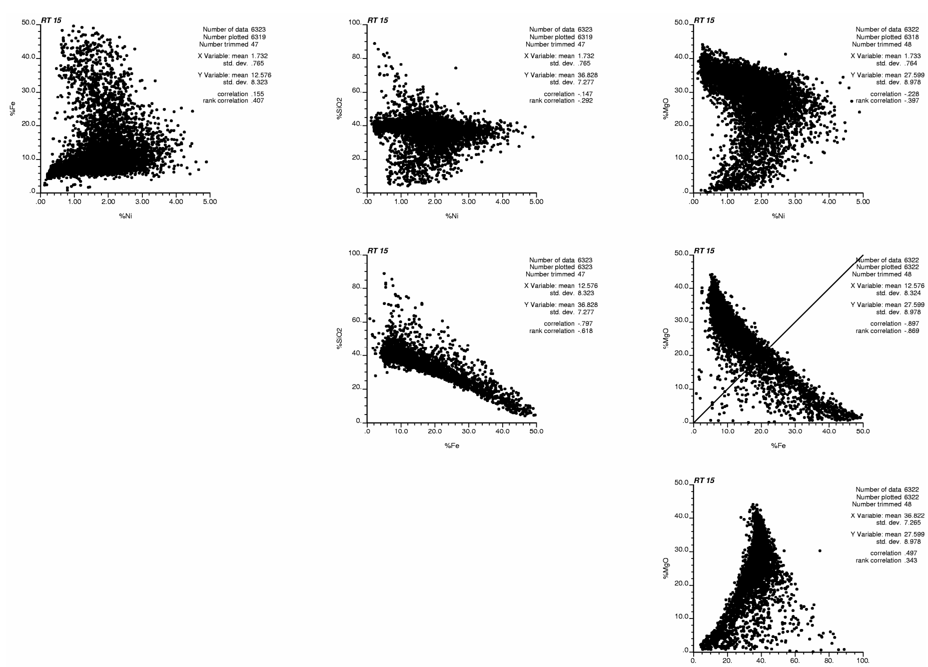

Figure 6: Scatterplots of grade variables in 15 (basic ETO).

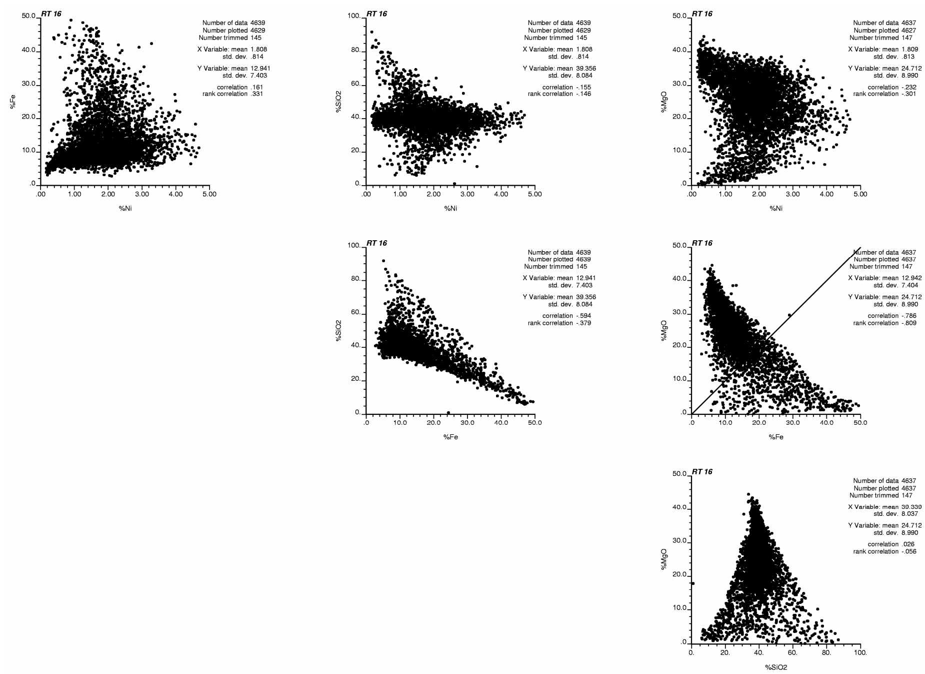

Figure 7: Scatterplots of grade variables in 16 (basic WTO).

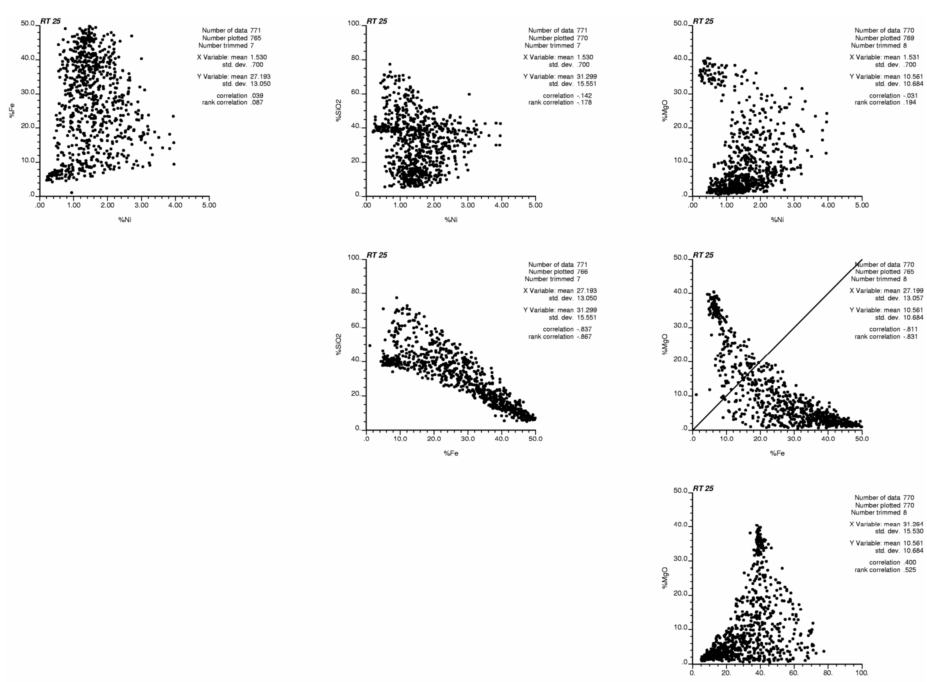

Figure 8: Scatterplots of grade variables in 25 (acid ETO).

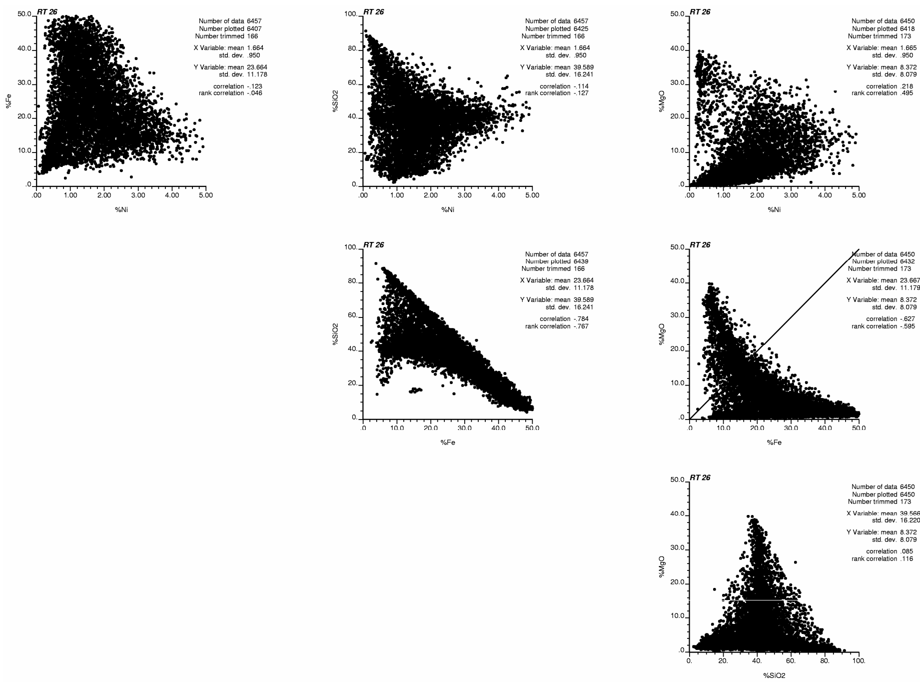

Figure 9: Scatterplots of grade variables in 26 (acid WTO).

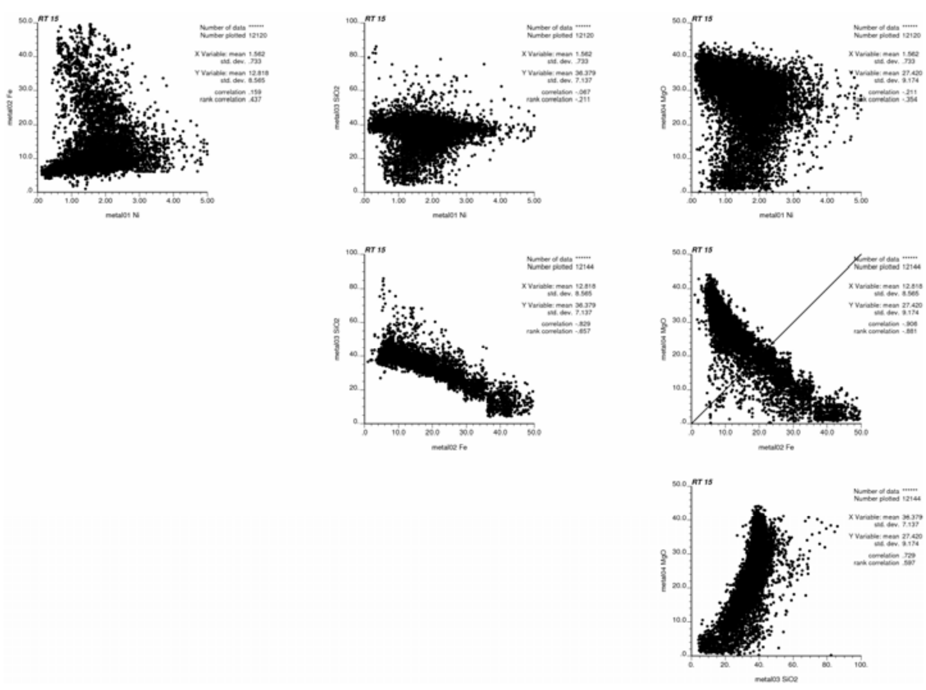

Figure 10: Scatterplots of simulated grade variables (1 in 100 plotted) in RT 15 (basic ETO) – to be compared with Figure 6.

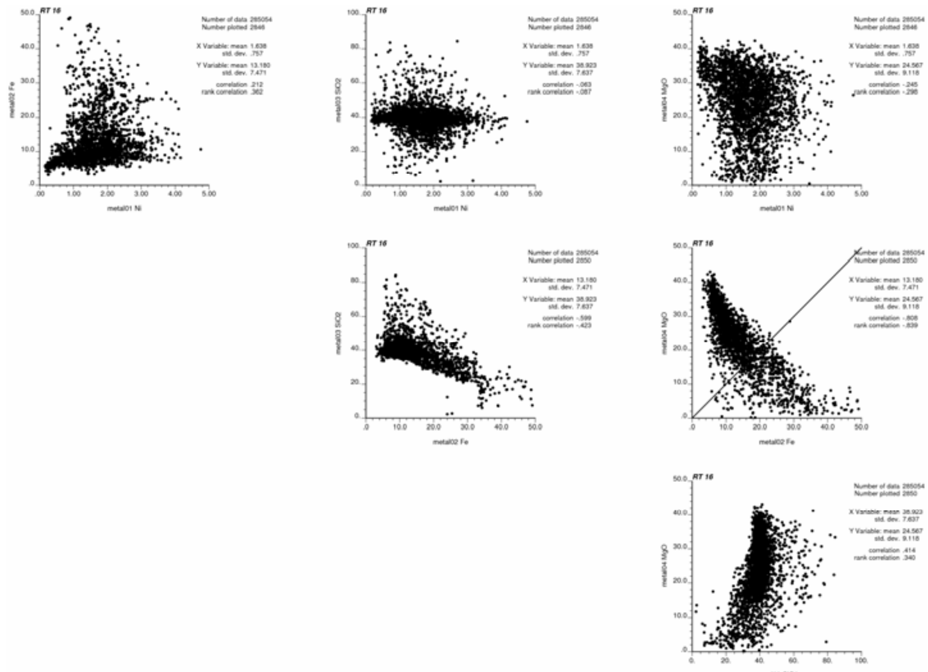

Figure 11: Scatterplots of simulated grade variables (1 in 100 plotted) in RT 16 (basic WTO) – to be compared with Figure 7.

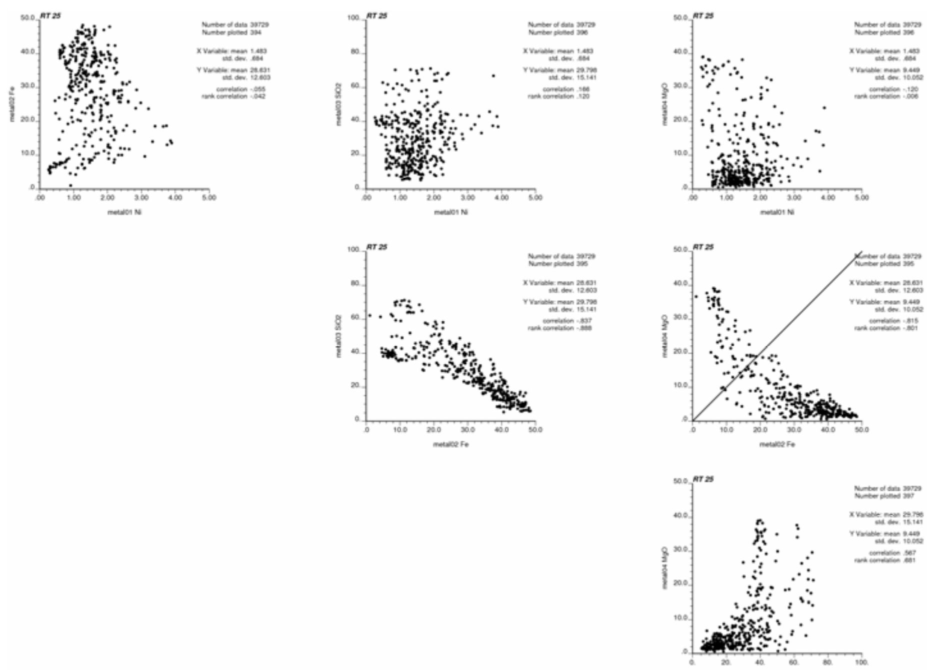

Figure 12: Scatterplots of simulated grade variables (1 in 100 plotted) in RT 25 (acid ETO) – to be compared with Figure 8.

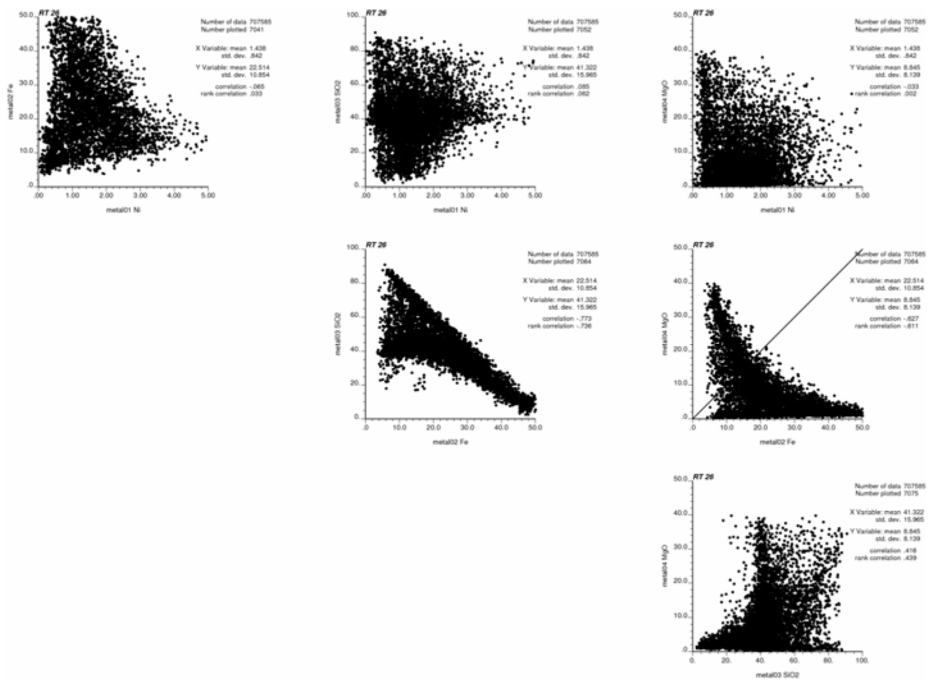

Figure 13: Scatterplots of simulated grade variables (1 in 100 plotted) in RT 26 (acid WTO) – to be compared with Figure 9.

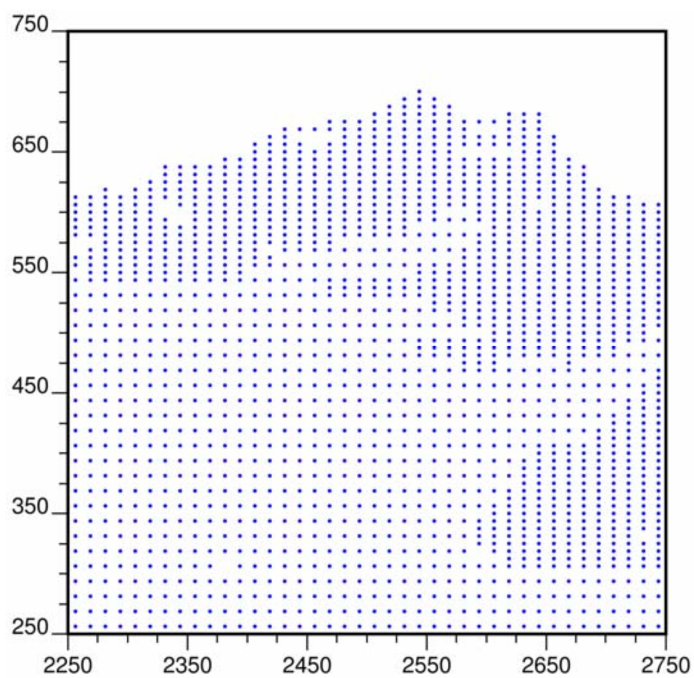

Figure 14: Close up map of the sample locations for the base case sampling.

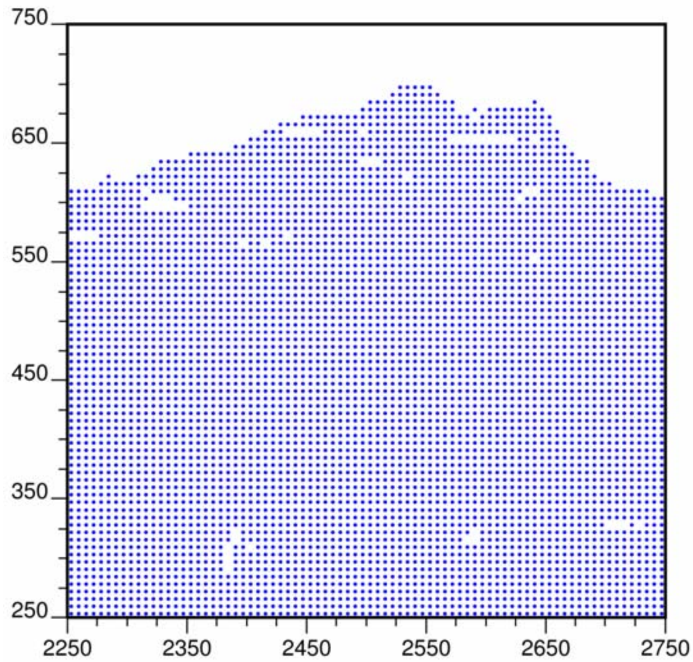

Figure 15: Close up map of the sample locations for the high selectivity sampling.

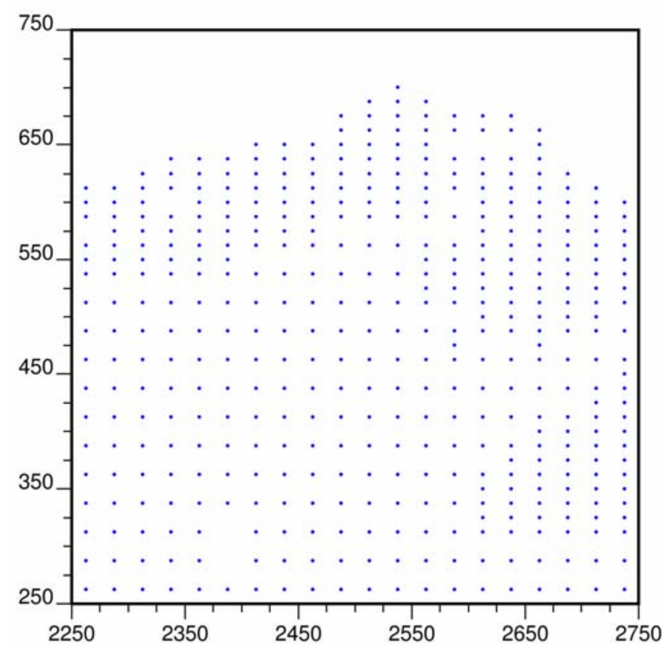

Figure 16: Close up map of the sample locations for the low selectivity sampling.

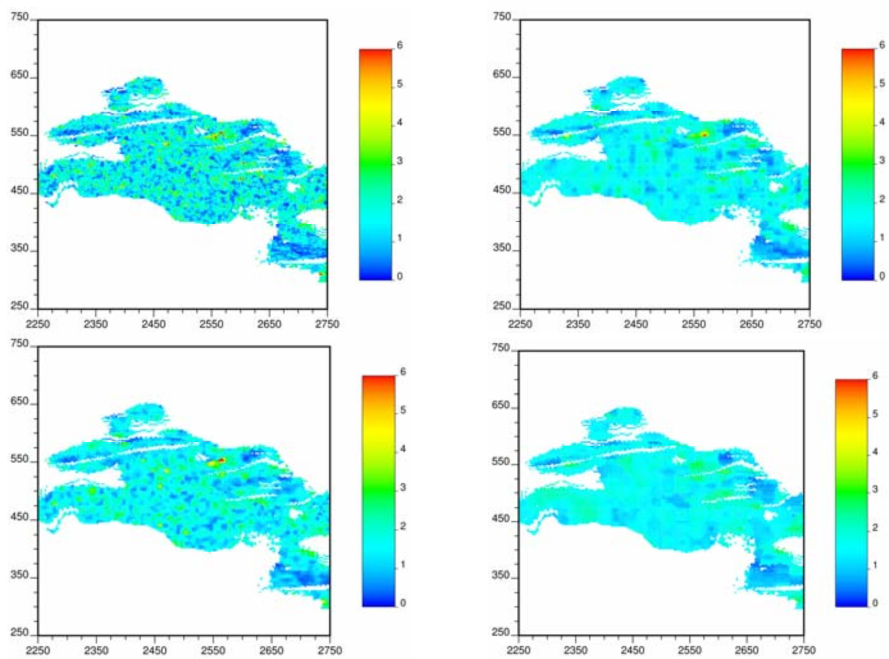

Figure 17: Simulated nickel grade in the small area (upper left). Grade control estimated nickel grade using the base case samples (upper right). Grade control estimated nickel grade using the high selectivity samples (lower left). Grade control estimated nickel grade using the low selectivity case samples (lower right).

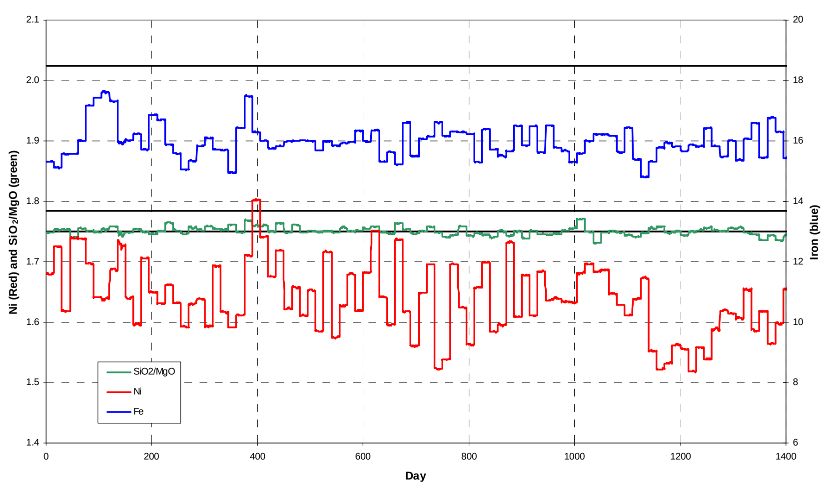

Figure 18: Simulated furnace for the base case. The green line represents the SMR, the red line is the nickel grade, and the blue line is the iron grade.

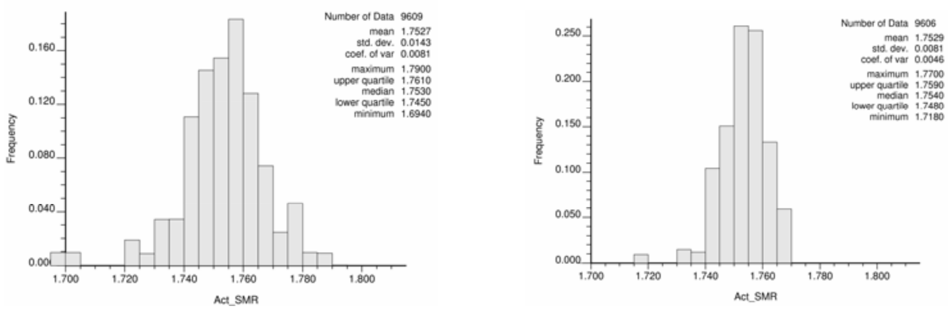

Figure 19: Histograms showing two different sets of furnace feed. The histogram on the left shows the variability in the furnace feed for the low selectivity grade control and the histogram on the right shows the variability for the base case grade control. The low selectivity case has almost twice the variability compared to the base grade control case.

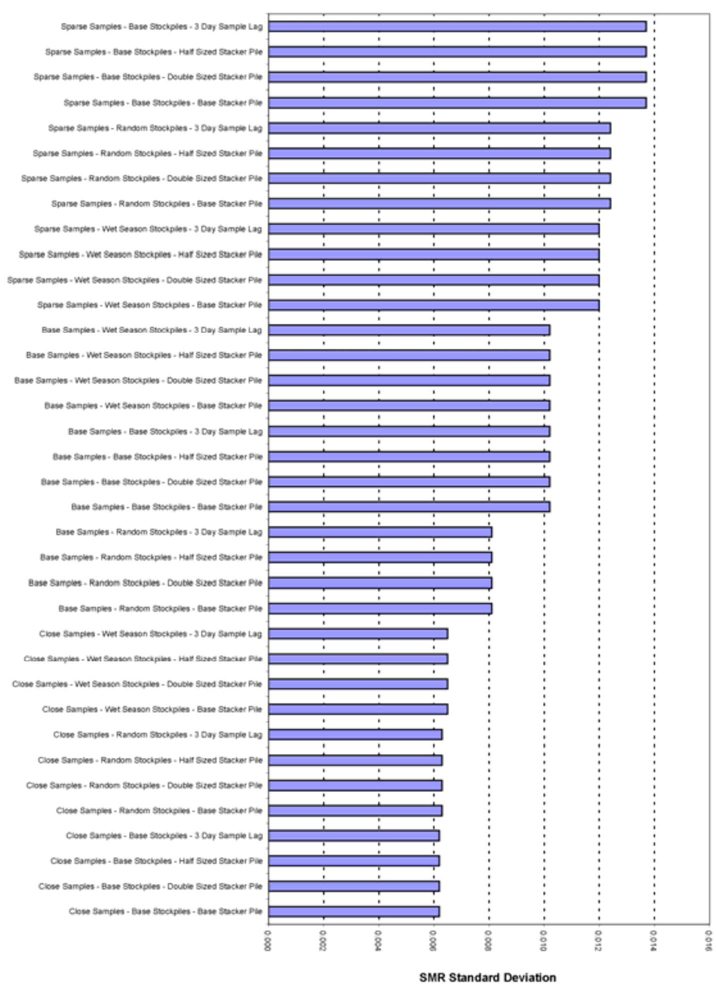

Figure 20: Sensitivity analysis results. The cases have been sorted from high SMR variability (at the top) to low SMR variability (at the bottom).

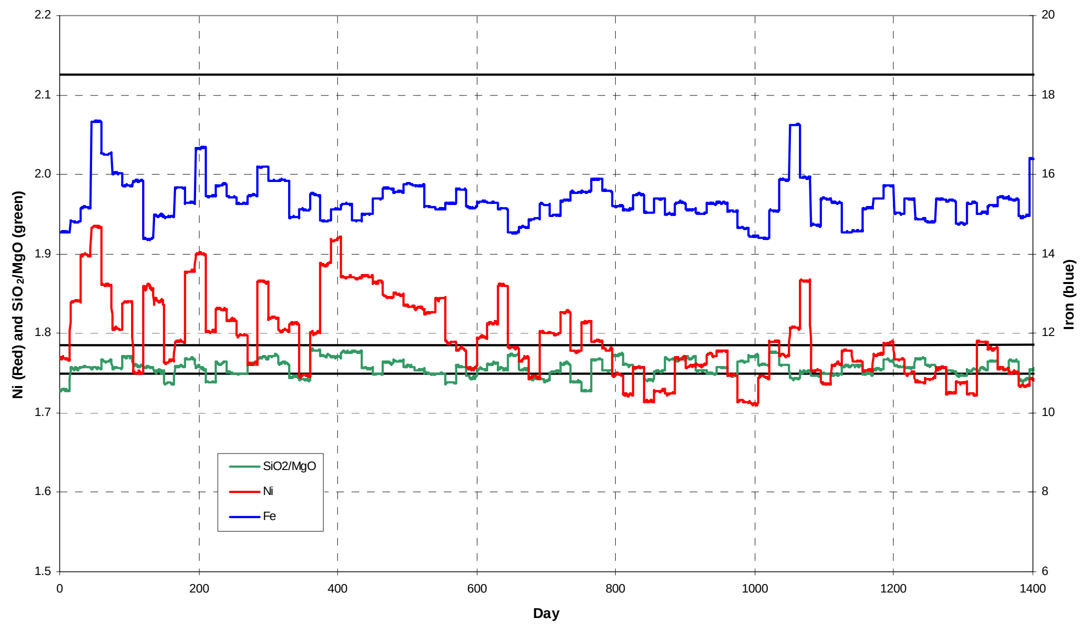

Figure 21: Furnace feed for the low selectivity samples, base case stockpiles, and base case stacker piles.

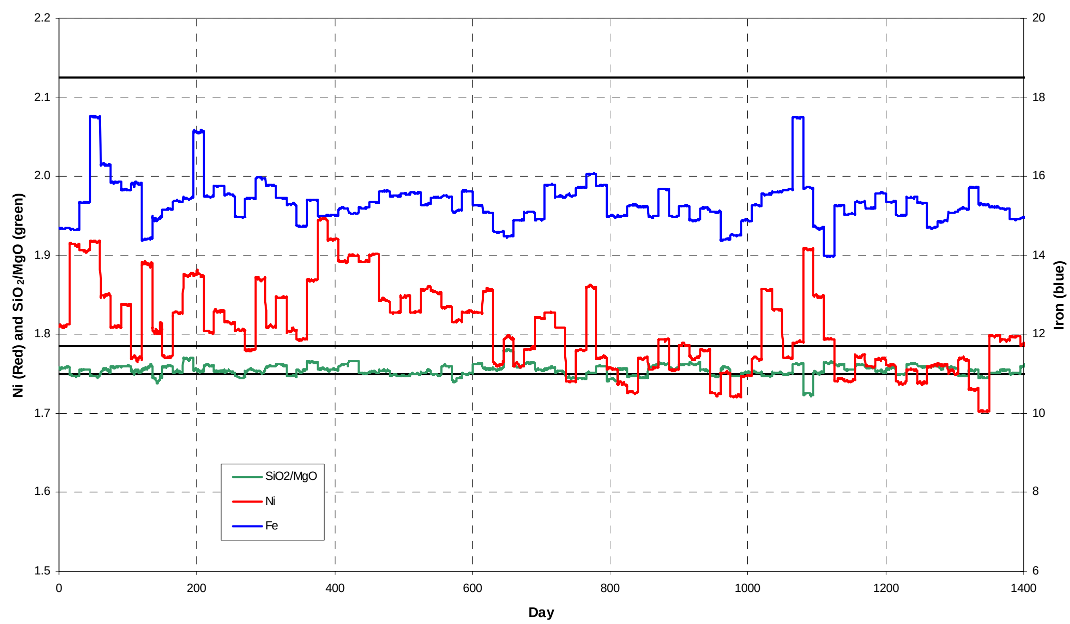

Figure 22: Furnace feed for the base case samples, base case stockpiles, and base case stacker piles.

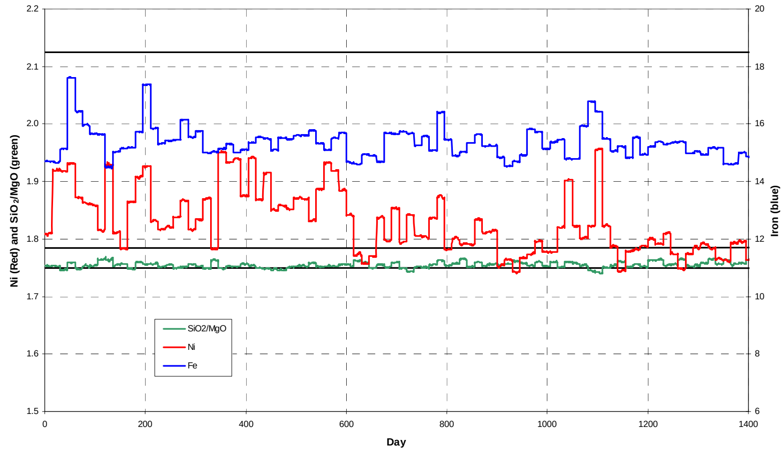

Figure 23: Furnace feed for the high selectivity samples, base case stockpiles, and base case stacker piles.

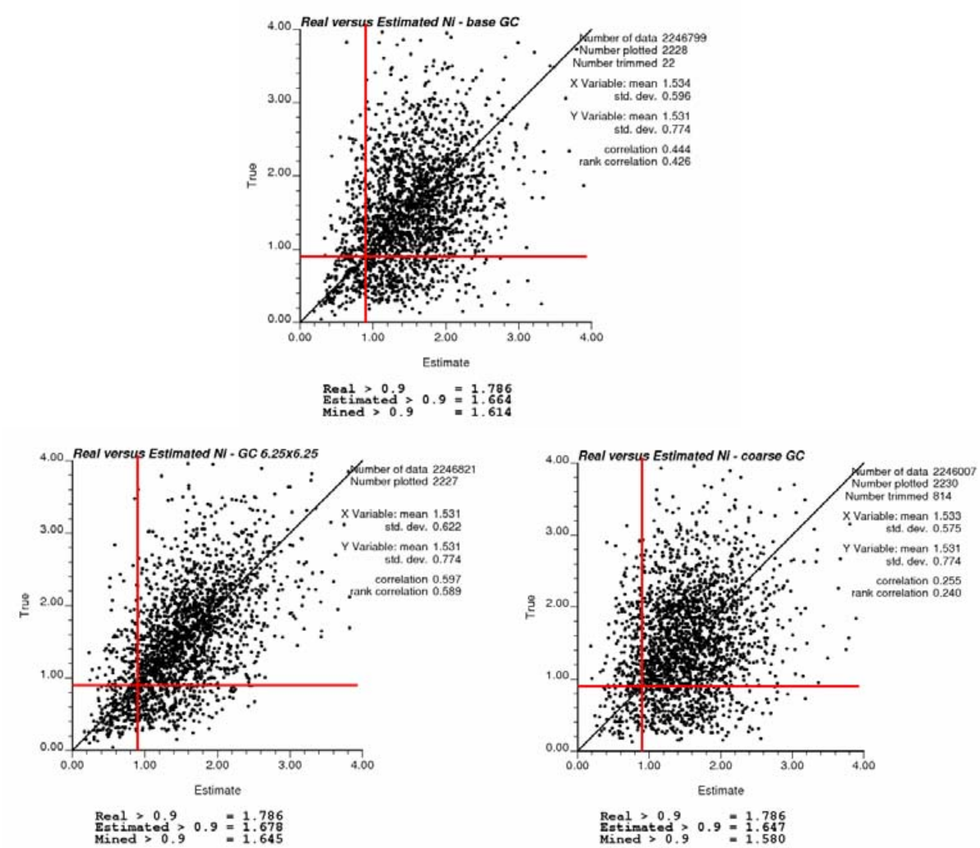

Figure 24: Check for the impact that the grade control drilling has on the nickel grade. The base case grade control drilling is on the top, the close spaced drilling is in the lower left and the coarse drilling is in the lower right.