Geostatistical methods for estimating iron, silica and alumina grades within the hardcap of the section seven iron deposit, Tom Price

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GEOSTATISTICAL METHODS FOR ESTIMATING IRON, SILICA AND ALUMINA GRADES WITHIN THE HARCAP OF THE SECTION SEVEN IRON DEPOSIT, TOM PRICE

Philip John Savory
BSc (Honours) Geology (UQ), Post Graduate Certificate in Geostatistics (ECU)

This thesis is presented in fulfilment of the requirements for the degree of Master of Science in Mathematics and Planning

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EDITH COWAN UNIVERSITY
ABSTRACT

Many iron ore deposits have a weathered zone (Hardcap) near the surface which is highly variable in grades. Estimating the amount of ore grade material (HG) in this zone is difficult as a result of this variability.

The Section Seven Deposit at Tom Price is largely mined out and has production data available in the form of grade blocks that were marked out during mining as HG and non-HG. Hardcap domains and a block model representing them were created and estimates were made from original exploration data using Ordinary Kriging, Global Change of Support, Indicator Kriging and Median Indicator Kriging techniques. The estimates were compared to the production data.

The production data total HG blocked out was 6.4 Mt and the best central estimator of ore was Ordinary Kriging (2.0 Mt). Indicator and Median Indicator Kriging E-type estimates of ore were very similar at ~ 1.6 Mt. The Global Change of Support estimate was 4.0 Mt. An effective way of seeing the excessive smoothing in the central estimates was to compare the grade tonnage curves.

All the central estimate of grades (OK, IK and Median IK E-type) were inaccurate and over smoothed. Given good quality samples and assays as well as sound estimation parameters the accuracy of these methods fundamentally comes down to the amount of data available to estimate from. There is insufficient data to get accurate estimates using these techniques.

The main information that Indicator Kriging provides is not the E-type estimate but an estimate of the distribution of grades for each block from which a pseudo-probability that the block is HG can be derived. The pseudo probability was used to create maps of HG at different probability levels and there was a good match visually and between the production data HG blocks and blocks that had a greater than 0 chance of being HG. In comparison to the maps of HG generated from Ordinary Kriging which feature very few HG blocks and many sub-HG blocks these are a great improvement. Median Indicator Kriging was just as effective as Indicator Kriging in this regard, which is an important point as the former is less work than the later. Quantitative reconciliation of the Median Indicator Kriging results against the production data showed that blocks with a
probability of 0.3 of being HG totalled 6.7 Mt and 49% of this matched HG production data.

This gives rise to a methodology as follows: If OK has been used in estimating hardcap and if the Global Change of Support estimate indicates that there is a risk of over-smoothing with regard to the HG cut-off then Median IK should be used to identify areas which have a chance of being HG and then deciding on the best way to take advantage of this information. Some possibilities would be to:

- target these areas for closer spaced drilling in order to generate an improved OK estimate;
- use the area defined above to sub-domain the hardcap and re-estimate using OK;
- target these areas for mining first as they have a good chance of being HG.
DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

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1 Introduction

Australia is the world’s third largest miner of iron ore (by tonnes mined) after China and Brazil (US Geological Survey, 2010) and most of this iron ore comes from the Pilbara region of Western Australia. The value of annual sales of iron ore from WA has grown from three billion dollars in 1995, 6.2 billion dollars in 2004, 11.3 billion dollars in 2005 to 62.8 billion dollars in 2011. In 2005 iron ore sales comprised 29 percent of the total revenue from the Mineral and Petroleum sector in WA. In 2011 this figure was 59 percent (Dept. of Mines and Petroleum, 2011).

Many iron deposits in the Pilbara have a weathered zone known as hardcap close to the surface. The hardcap is variable in its thickness, lithology and grade attributes and these variations can occur over very short distances (less than five metres). The resource within the hardcap may make up a significant percentage of the total resource and it normally makes up a large percentage of the resource mined initially.

Each deposit being mined is represented by a resource model and many attributes, including grades, of the mineralisation are estimated into the model using geostatistical methods. Estimated tonnes of ores from hardcap have reconciled poorly against the actual tonnes realised through mining, which represents a serious problem as mining professionals require that resource models be reasonably accurate so they can plan mining effectively.

1.1 Aim and Objectives

The aim of this thesis is to investigate how to use information gained from Ordinary Kriging, Global Change of Support (GCoS), Indicator Kriging (IK) and Median IK estimation in defining iron ore resources in hardcap domains. Of particular interest is the ability of each method to categorise selective mining units as High Grade (HG) Ore ($\geq 60\%$ Fe) as this is the most valuable ore.

A three dimensional block model will be created of the hardcap domains in the Section Seven deposit at Tom Price. The domains will be estimated using Ordinary Kriging, GCoS, IK and Median IK. The deposit is largely mined out and production data in the form of grade blocks created from close spaced blasthole data are available for comparison to the estimates.
Ordinary Kriging is the usual method used to estimate domains. GCoS provides a global estimate for domains and will be used to check the estimates for excessive smoothing at the 60% cut-off. IK (and Median IK) do provide more information than OK in the form of a ccdf estimated for each block and this may be interpreted as the probability of a block being HG.

The objectives of this thesis are to:

- Assess the information provided by the techniques of OK, GCoS and IK (including Median IK) against each other and the production data.
- Examine the extra information provided by IK and Median IK and determine how it may be exploited in estimating HG.
- Devise a methodology to estimate the HG distribution in the hardcap.

1.2 Iron Ore

Rio Tinto operates several iron ore mines in the Pilbara region of Western Australia (see Figure 1-1). These mines produce iron ore Lump and Fines for sale, mainly to Chinese and Japanese markets. Lump iron ore is iron ore greater than or equal to 6.3mm but less than 40mm in diameter, Fines iron ore is all ore smaller than this. The iron ore from different mines is blended at Dampier to meet market specifications.

The chemical nature of the iron products sold is close to pure hematite (Fe₂O₃, 70% Fe). There are impurities contained in the ore that are important to miners and customers and two are Alumina Oxide (Al₂O₃) and Silica or Silicon Dioxide (SiO₂). A high level of both these impurities in the ore used in the blast furnace reduces the efficiency of the furnace (because more flux is required) and more waste by-product (slag) is produced.
Estimates of Fe, SiO₂, Al₂O₃, and other chemical and physical attributes are made into resource models that represent the deposit. Whether the mineralisation is estimated to be ore or waste is determined by the magnitude of these attributes. Depending on the nature of the orebody the attributes that are used to differentiate ore from waste may vary slightly between deposits although Fe is always a consideration. For the iron deposits at Tom Price the cut-off grade for High Grade Ore (HG) is Fe greater than or equal to 60%.

1.3 Literature Review

Geostatistics arose from the need to estimate mining attributes at locations where they were unknown using known data from other locations. In this simplest regard the science of geostatistics has probably existed from the very first ancient miners. In the late 1950s and early 1960s Danie Krige and Georges Matheron, both mining engineers, gave a far more detailed framework for the science of geostatistics. Matheron introduced the concepts of the regionalised variable, the variogram, extension variance and kriging (Matheron, 1963). Kriging, as defined by Matheron, “consists in estimating the grade of a
panel by computing the weighted average of available samples, some being located inside others outside the panel”.

Early techniques based on the works of Krige and Matheron focussed on linear estimation methods such as simple kriging and ordinary kriging where the weights assigned to the sample locations inside the estimation neighbourhood are independent of the data values at these locations. Ordinary kriging (OK) provides a single estimate at locations that minimises the estimation variance and conditional bias (Matheron, 1963). A drawback is that OK may smooth the grade too much with respect to grade cut-offs and thus provide an unrealistic estimate of tonnes and grades at these cut-offs (Krige, 1996). A related drawback is that the data spacing may be wide compared to the selective mining unit (SMU). The SMU is the minimum sized mining block that can be expected to be recovered from a mining operation, fundamentally, this is a function of mining method and equipment. A large number of authors have warned against the problems, involving over-smoothing, associated with estimating into blocks that are much less than half the drill grid spacing, (Armstrong and Champigny, 1989; Journel, 1983; Journel and Huijbregts, 1978; Krige, 1994, 1996; Rivoirard, 1994).

A large amount has been written on the implementation of ordinary kriging and guiding practitioners with ore resource estimation (Armstrong, 1998; Coombes, 2008; Goovaerts, 1997; Isaaks and Srivastava, 1989; Krige, 1994). The 1994 paper by Krige sets out some of the basic necessities including a good geological model and subdivision of the orebody into geologically homogenous domains. For estimation Krige stresses that any kriging technique which does not access enough data to eliminate conditional biases is suboptimal and does not use all available data to best advantage. Krige also discusses the importance of validating the model estimates using follow-up values from mining or reconciliation.

The literature on search size is somewhat conflicting. Some guidelines on search size selection for OK were published by Vann et al., 2003 in a paper titled Quantitative Kriging Neighbourhood Analysis. In this paper the authors assert that the selection of search neighbourhood and parameters such as number of composites used are very important in kriging where the quality of estimate locally is important. Too large a neighbourhood may result in excessive negative weights and/or excessive smoothing and too small a neighbourhood may result in very high conditional bias. The authors discuss
four criteria which they believe need to be considered in setting the search neighbourhood and they are:

1. The slope of regression \( Z_v/Z_v^* \) (Where \( Z_v \) is the true grade of a block and \( Z_v^* \) is the estimated grade of the block);

2. The weight assigned to the mean for a simple kriging (SK);

3. Percentage Blocks Filled;

4. The kriging variance;

Isaaks (2005) in the paper *The Kriging Oxymoron: A conditionally unbiased and accurate predictor* discusses the impossibility of achieving an estimate which is both unbiased and provides accurate predictions of tonnes and grades above a cut-off grade. Isaaks suggests that the end use of the model be considered either:

Type 1 Models used for long term planning;

Type 2 Models that will be mined from or grade control models;

Isaaks states that it is only worth minimising conditional bias if the model is Type 2. If a model is Type 1 then it is irrelevant whether conditional bias exists or not. The model in this thesis is primarily of Type 1 however is also partly of Type 2. This means that minimising conditional bias will be of some consideration in selecting search neighbourhood size.

Any selection of search neighbourhood also should take into account the relevance of nearby samples (Isaaks and Srivastava, 1989). Sound geological interpretation is important requiring good quality domains for estimating in the model. In addition to this an understanding of the variability within domains is also important.

It can be concluded from the literature that search domain size and orientation can have a large impact on the results of any estimation. It is possible to select a less than optimal domain, for example one that does not result in estimates for all the blocks or one with very high negative weights, unless the criteria by which the neighbourhood chosen are examined. It can also be foreseen that without viewing the results of different neighbourhood search tests that the quality of the estimates may not be fully understood. An example of this would be if the minimum number of samples was not tested over a range then it might not be understood how many blocks are being estimated at points on this range.
The term “recoverable reserves” refers to the quantity and grade of resources that may be recoverable from a mineral deposit. The global ‘discrete Gaussian model’ (DGM) of change of support (Journel and Huijbregts, 1978) is a method of estimating global resources. The DGM is based on the idea that after the raw sample support distribution is transformed to a Gaussian distribution Krige’s relation may be used to change this distribution to block support. The key assumptions are:

- The resultant transforms are bivariate Gaussian (the Gaussian sample values and block values are correlated);
- The spatial grade distribution moves from lower values to higher values in a relatively continuous way.

Other important assumptions are:

- The samples are representative of the domain and the variogram model is robust;
- Free selection of SMUs so that all SMUs may be mined so long as they are above the cut-off;

A benefit of using the DGM is that it is able to take into account the information effect.

Some limitations of OK were discussed previously and partially in response to these and more generally in response to the limitations of linear methods Journel introduced the non-linear, nonparametric indicator approach as a step forward for Geostatistics in 1982 (Journel, 1982). He also wrote a more developed article in 1983 (Journel, 1983). In a nutshell Indicator Kriging (IK) is a non-linear technique allowing the estimation of probabilities of exceeding pre-specified cut-offs without the smoothing effect of linear interpolation. The main improvements over parametric methods Journel cited were:

1. The allowance of more comprehensive structural analysis of the data;
2. More robustness of the experimental semivariograms to extreme outlier data values. Highly variable attributes may be handled without having to trim off important high or low value data.
Problems arise with linear estimation methods when dealing with sample data that have long-tailed distributions with coefficients of variation in the range of two to five (Journal, 1983). This sort of data produces erratic experimental semivariograms. Indicator values are either 0 or 1 depending on their value with regard to a cut-off $z_k$ and thus the experimental indicator semivariograms are safeguarded against extreme values within long tails. The best defined experimental indicator semivariograms will correspond to thresholds $z_k$ close to the median of $Z$. Indicator Kriging (IK) allows risk-qualified estimation of the conditional cumulative distribution function (ccdf) from which the local recoverable reserves can be estimated. Issues regarding the use of multiple indicators regarding sequential descending indicators requiring a greater or equal cumulative proportion of metal than prior indicators are discussed.

A summary paper on IK by Vann et al., (2000) presents the underlying concepts, motives associated with non-linear estimation of mineral resources in the mining industry with a major focus on IK (due to it being the most commonly applied non-linear estimation method). It is pointed out that many mineral resource sample data sets are highly skewed, presenting experimental semivariograms with a high relative nugget. The limitations of estimating block grades using linear estimation techniques such as: Inability to model the distribution of grades; and de-skewing of the sample histogram and variance reduction (together known as smoothing); are noted. The best possible estimation of a function of the grade is the conditional expectation and non-linear techniques estimate this conditional expectation. Non-linear estimation techniques in current use in the mining industry are listed as Disjunctive Kriging (DK), Indicator Kriging (IK), Probability Kriging (PK), Lognormal Kriging (LK), Uniform Conditioning (UC), Residual Indicator Kriging (RIK). The theory behind indicator kriging is discussed. The authors note that within the area of recoverable resource estimation IK is the most widely used method and is practical to implement. The practical difficulties are also pointed out and emphasised due to their impact on reliability of results. These are stated as:

1. Evenly selected threshold e.g. deciles may not provide the necessary resolution in important parts of the conditional cumulative distribution function. The suggested alternative is to include additional discretisation in these critical sections or define the thresholds so that each threshold contains equal proportions of metal.
2. The tail(s) of the distribution may contain few samples so selection of the shape of the ccdf from the uppermost and lowermost thresholds to the limit is important but is subjective.

3. E-type estimates of the grade can have significant consequences on the grades of the richest zones of the orebody.

4. The experimental indicator semivariograms for higher thresholds tend towards pure nugget. The authors suggest a possible solution with such semivariograms is to use a large search neighbourhood, in order to avoid conditional bias. They note the side-effect of this is then smoothing in these classes.

5. The time taken to do experimental indicator semivariograms and models can lead to short-cuts.

6. Order relation problems arise when models of the experimental semivariogram are inconsistent from one cut-off to the next. This may result in more metal being estimated in a higher cut-off than for a lower cut-off which is impossible. The authors emphasise the dangers of black box software corrections to this problem as the details of any correction algorithms should be reported in the resource report. The suggested ways in which order relation problems may be reduced are by ensuring:
   
   i. The experimental indicator semivariogram models are consistent. The most obvious example of this consistent modelling being Median Indicator Kriging (Median IK), however this model is rarely going to agree with the experimental semivariograms at every threshold
   
   ii. The search neighbourhoods are identical. However it is noted that this is only a good plan if the experimental semivariograms are the same shape or are proportional.
   
   iii. As cut-offs increase at least one datum in the search neighbourhood will change from 0 to 1.

7. Change of support is not inherent in the MIK method but is applied as a post-processing step. A warning is sounded with regard to using the affine
correction (no deskewing of the distribution between samples and blocks) particularly when dealing with sample data with a high nugget or a pronounced short-scale structure.

The authors then go into a discussion into the geological situations where MIK should be more applicable. Situations where there are no “border effects” or where there are hard boundaries between grades are more conducive to the application of MIK (the authors recommend considering RIK over MIK due to its improved change of support compared to MIK). Where grade boundaries are more transitional or diffuse MIK does not work as well. The method suggested for these situations is Uniform Conditioning. An objective way of assessing the data with regard to the criteria above is presented. The two key questions to be answered to address the question MIK – Is it suited to my deposit? are:

1. What are the relations between the experimental indicator semivariograms and experimental indicator cross variograms in the deposit;

2. Is there significant deskewing of the histogram when changing support.

A paper that covers estimation techniques in iron ore is by De-Vitry et al., (2007). In this paper the authors point out that when only wide-spaced drilling (relative to block size) is available, properly implemented linear estimation (including ordinary kriging) may predict grade tonnage relationships that are over-smoothed compared to actual production. Non-linear estimation and conditional simulation are alternative geostatistical approaches that can provide more reliable estimates of the recoverable tonnage and grade from wide-spaced drilling. Implementing non-linear techniques is costly and it would be important to first understand if there would be a benefit of doing so.

In order to help determine if there would be a benefit the authors recommend a well-established non-linear geostatistical approach, the global ‘discrete Gaussian model’ (DGM) of change of support, as a tool to establish whether moving from linear to non-linear estimates will materially improve results. They also point out other practical considerations to bear in mind. Firstly are the users of the model able to deal with the more complicated non-linear estimate or simulation. Secondly the required use of the model with regard to project stage of development e.g. it may be worthwhile but it may be better waiting for further drilling.
This thesis will utilise elements of the methodology discussed above in assessing whether a non-linear estimate may improve results. In particular a DGM change of support estimate will be generated to compare with the OK estimate. If these estimates are significantly different then the use of IK should provide a better result.

1.4 Outline

The first chapter of the thesis introduces the thesis and give the background behind the study in terms of the iron ore industry and geology. Chapter 2 sets out the mathematical background including the theory behind the experimental semivariogram, ordinary and indicator kriging and Krige’s relation relevant to this thesis.

From Chapter 3 onwards the material presented is specific to the Section Seven Deposit at Tom Price. In Chapter 3 the geology of the Section Seven iron ore deposit and the data available for modelling are presented. The preparation of the data for kriging estimation and exploratory data analysis including semivariogram modelling is discussed in Chapter 4. In Chapter 5 search distance selection is discussed before moving on to the estimation methods: ordinary kriging and change of support (Krige’s relation) and Indicator Kriging. In Chapter 6 the various estimation results are compared to actual mine grade blockouts from blasthole samples in order help assess which method has performed best. Conclusions to the study are contained in Chapter 7.
### Abbreviations and Common Notation

<table>
<thead>
<tr>
<th>Abbreviation/Term</th>
<th>Meaning</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>BIF</td>
<td>Banded Iron Formation</td>
<td></td>
</tr>
<tr>
<td>Block</td>
<td>The fundamental building unit of the model.</td>
<td>Blocks in this thesis are 30 m x 30 m x 5 m.</td>
</tr>
<tr>
<td>cdf</td>
<td>cumulative distribution function</td>
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<tr>
<td>ccdf</td>
<td>Conditional cumulative distribution function</td>
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<tr>
<td>DGM</td>
<td>Discrete Gaussian Model</td>
<td></td>
</tr>
<tr>
<td>E-type</td>
<td>Conditional expectation estimate</td>
<td></td>
</tr>
<tr>
<td>GCoS</td>
<td>Global Change of Support</td>
<td></td>
</tr>
<tr>
<td>HG</td>
<td>High Grade</td>
<td>Material Greater than or equal to 60% Fe.</td>
</tr>
<tr>
<td>IK</td>
<td>Indicator Kriging</td>
<td></td>
</tr>
<tr>
<td>Median IK</td>
<td>Median Indicator Kriging</td>
<td></td>
</tr>
<tr>
<td>OH</td>
<td>Open Hole</td>
<td>A drilling sample method</td>
</tr>
<tr>
<td>OK</td>
<td>Ordinary Kriging</td>
<td></td>
</tr>
<tr>
<td>QKNA</td>
<td>Quantitative Kriging</td>
<td>Neighbourhood Analysis</td>
</tr>
<tr>
<td>RC</td>
<td>Reverse Circulation</td>
<td>A drilling sample method</td>
</tr>
<tr>
<td>RF</td>
<td>Random function</td>
<td></td>
</tr>
<tr>
<td>RV</td>
<td>Random variable</td>
<td></td>
</tr>
<tr>
<td>SMU</td>
<td>Selective Mining Unit</td>
<td>The minimum sized mining unit that can be expected to be recovered from a mining operation. SMU’s in this thesis are 15 m x 15 m x 5 m</td>
</tr>
<tr>
<td>Abbreviation/Term</td>
<td>Meaning</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>Range parameter</td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>Study area</td>
<td></td>
</tr>
<tr>
<td>$C(h)$</td>
<td>Stationary covariance of the RF</td>
<td></td>
</tr>
<tr>
<td>$E{\cdot}$</td>
<td>Expected value</td>
<td></td>
</tr>
<tr>
<td>$F(z)$</td>
<td>Cumulative distribution function of a RV</td>
<td></td>
</tr>
<tr>
<td>$F(u; z_k)(n)$</td>
<td>Non-stationary conditional cumulative distribution function of the</td>
<td></td>
</tr>
<tr>
<td>$i(u; z)$</td>
<td>Separation vector</td>
<td></td>
</tr>
<tr>
<td>$I(u; z_k)$</td>
<td>Binary indicator RF at location $u$ and for threshold $z_k$</td>
<td></td>
</tr>
<tr>
<td>$i(u; z)$</td>
<td>Binary indicator value at location $u$ and for threshold $z$</td>
<td></td>
</tr>
<tr>
<td>$K$</td>
<td>Number of threshold values $z_k$</td>
<td></td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Weights applied to samples</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{ok}^\alpha$</td>
<td>Ordinary kriging weight associated to $z$-datum at location $u_\alpha$</td>
<td></td>
</tr>
<tr>
<td>$m$</td>
<td>Stationary mean of the RF $Z(u)$</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>Number of sample values $z(u_\alpha)$</td>
<td></td>
</tr>
<tr>
<td>$\sigma^2$</td>
<td>Variance of the RV $Z$</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>The slope of the linear regression of $Z_\psi$ on $Z_\psi^*$</td>
<td></td>
</tr>
<tr>
<td>$S_n$</td>
<td>The set of $n$ sample measurements</td>
<td></td>
</tr>
<tr>
<td>$u$</td>
<td>Coordinate vector</td>
<td></td>
</tr>
<tr>
<td>$u_\alpha$</td>
<td>Datum location</td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td>Blocks</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>Samples</td>
<td></td>
</tr>
<tr>
<td>$Var{\cdot}$</td>
<td>Variance</td>
<td></td>
</tr>
<tr>
<td>$\gamma(h)$</td>
<td>Stationary semivariogram of the RF $Z(u)$ for lag vector $h$</td>
<td></td>
</tr>
<tr>
<td>$\hat{\gamma}(h)$</td>
<td>Experimental semivariogram modelled from the sample data</td>
<td></td>
</tr>
<tr>
<td>$Z_{ok}^*(u)$</td>
<td>The ordinary kriging estimator of $Z(u)$</td>
<td></td>
</tr>
<tr>
<td>$Z(u)$</td>
<td>Generic continuous RV at location $u$</td>
<td></td>
</tr>
<tr>
<td>$z$</td>
<td>Continuous attribute</td>
<td></td>
</tr>
<tr>
<td>$z_k$</td>
<td>$k$th threshold value for the continuous attribute $z$</td>
<td></td>
</tr>
<tr>
<td>$z(u)$</td>
<td>True value at unsampled location $u$</td>
<td></td>
</tr>
<tr>
<td>$z(u_\alpha)$</td>
<td>$z$ datum value at location $u_\alpha$</td>
<td></td>
</tr>
<tr>
<td>$Z_\psi$</td>
<td>True block values</td>
<td></td>
</tr>
<tr>
<td>$Z_\psi^*$</td>
<td>Estimated block values</td>
<td></td>
</tr>
</tbody>
</table>
2 Geostatistics Background

This chapter gives a brief overview of the underlying statistical model and the estimation methods used in this project. The notation followed is from Goovaerts (1997) and the reader is referred to this text for more detail.

2.1 The Random Function Model

The framework used in this project rests on the Random Function Model.

Let \( \{z(u), u \in A\} \) denote the population, the set of all values of the attribute \( z \) over study area \( A \), and let \( S_n = \{z(u_\alpha), \alpha = 1, ..., n, u_\alpha \in A\} \) be the set of \( n \) sample measurements of attribute \( z \) over the study area \( A \).

It is desired to estimate the values of \( z \) at unsampled locations \( u \) in \( A \). For spatial data it is not possible to develop a deterministic model that will estimate attribute values at points where they are unknown because of our incomplete knowledge of a complex process, e.g. orebody formation. Thus a probabilistic model is used. This approach provides a set of possible outcomes for the attribute value at each point where the value is unknown along with the corresponding probabilities for these outcomes. Most information in modelling \( z(u) \) comes from \( S_n \) but relevant deterministic information such as the rock types may be used if relevant.

Within the probabilistic framework a random variable is any function or mechanism that assigns a numerical value to each possible outcome. Random variables may be discrete or continuous. Continuous random variables have a continuous range of possible outcomes and these are the ones considered here.

In the random function model the sample value \( z(u_\alpha) \) is regarded as a realisation (value) of a random variable \( Z(u_\alpha) \). Similarly, \( z(u) \) is regarded as a realisation of a random variable \( Z(u) \).

The random function is then defined as the set of these random variables. Hence \( RF = \{Z(u), u \in A\} \). Note the random variables \( Z(u), u \in A \) cannot be assumed to be independent.

In classical statistics repeat measurements allows for the estimation of the distribution of a given random variable. While viewing spatial data within a probabilistic
framework there are no repeat measurements: usually there is only one value at each sample location. To bridge this gap with regard to inferring the covariance statistic pairs of data at a distance or lag of \( h \) apart are used within the study region \( A \). The pairs of random variables \( \{Z(u_\alpha), Z(u_\alpha + h); \alpha = 1, \ldots, n\} \) are pooled regardless of their location and this calls for some assumption to be made about the stationarity of the random function. For the random function model \( \{Z(u), u \in A\} \) to be assumed to be stationary within \( A \) the distribution must be translation invariant. This cannot be checked from the limited data in \( S_n \). One possibility is then to assume that the random function is second order stationary. This occurs when:

- The expected value or mean \( E[Z(u)] \) exists and is invariant within \( A \);
- The covariance \( C(h) = E[Z(u).Z(u + h)] - E[Z(u)] \cdot E[Z(u + h)] \) exists and depends only on the separation vector \( h \).

In practice, the assumption of second order stationarity is not always appropriate and the weaker condition of intrinsic stationarity is assumed. This occurs if the random function increments \( Z(u) - Z(u + h) \) are second order stationary. This now allows for the mean and covariance to vary so long as they vary in a way that this condition is met.

If the conditions of intrinsic stationarity are met then the following two relations are valid:

1. \( E[Z(u) - Z(u + h)] = 0 \): The mean of the increment is 0;
2. \( 2\gamma(h) = Var[Z(u) - Z(u + h)] = E[(Z(u) - Z(u + h))^2] \): \( 2\gamma(h) \) is called the variogram and \( \gamma(h) \) is referred to as the semivariogram.

\( Z(u) - Z(u + h) \) describes the spatial variation of the random function. The theoretical semivariogram is calculated at each lag as half the average squared difference of the values of each data pair:

\[
\gamma(h) = \frac{1}{2} E[(Z(u) - Z(u + h))^2] \]

If the conditions of second order stationarity are met then the following two relations are also valid:

1. \( Var[Z(u)] = E[(Z(u) - Z(u + h))^2] = C(0) \): The variance of the random function equals the covariance with \( h = 0 \) and it is constant;
2. \( \gamma(h) = C(0) - C(h) \): The semivariogram of the random function can be inferred from the covariance.

Note also \( C(h) \to 0 \) for \( |h| \to \infty \) and \( \gamma(h) \to C(0) \) for \( |h| \to \infty \)

Note that if a random function is second order stationary then it is intrinsic stationary but the converse is not true. The relation \( \gamma(h) = C(0) - C(h) \) can only be used if the variance is finite or the semivariogram is bounded.

2.2 The Experimental Semivariogram and Covariance Functions

In practice the theoretical semivariogram \( \gamma(h) \) is modelled from the experimental semivariogram which is calculated from the sample data. This modelling involves fitting a piecewise continuous function to the experimental data so that a value may be given to the function for any \( h \). The experimental semivariogram \( \hat{\gamma}(h) \) is defined as.

\[
\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{\alpha=1}^{N(h)} (z(u_{\alpha}) - z(u_{\alpha} + h))^2
\]

where, \( N(h) \) is the total number of pairs of data locations for lag \( h \), \( z(u_{\alpha}) \) is the sample value of the datum at location \( u_{\alpha} \) and \( z(u_{\alpha} + h) \) that at location \( u_{\alpha} + h \).

The experimental semivariogram then may be shown graphically as a sequence of points each of which is a measure of the covariance between sample pairs at a given lag. Typically the experimental semivariogram function increases with distance (i.e. samples usually become more dissimilar the further they are apart). The vector \( h \) accounts for both distance and direction and so the functions \( C(h) \) and \( \gamma(h) \) are anisotropic if they depend on both or isotropic if they just depend on distance.

In kriging the equations to be solved for the weights are expressed in terms of covariance function rather than semivariogram. The continuous function that is fitted to the experimental semivariogram must be conditionally negative definite. The equivalent covariance function must be conditionally positive definite. This provision exists so that the variance of any weighted combination of the random variables is non-negative (if the weight is denoted by \( \lambda \), then the provision may be written:

\[
Var \left( \sum_{\alpha=1}^{n} \lambda_{\alpha}(u) Z(u_{\alpha}) \right) \geq 0
\]
Some of the models that may be fitted to the semivariogram are shown here in terms of
the covariance. Note that these models are bounded so use can be made of the relationship
$C(h) = C(0) - \gamma(h)$. The range in these functions is the distance beyond which the
covariance function is 0.

**Nugget effect model**

$$c(|h|) = \begin{cases} 1 & \text{for } |h| = 0 \\ 0 & \text{for } |h| > 0 \end{cases}$$

**Spherical model with range $a$.**

$$c(|h|) = \begin{cases} 1 - \frac{3|h|}{2a} + \frac{1}{2a^3}|h|^3 & \text{for } 0 \leq |h| \leq a \\ 0 & \text{for } |h| > a \end{cases}$$

### 2.3 Ordinary Kriging

Ordinary Kriging (OK) estimates unknown attribute values by applying weights to
available sample values and computing a linear combination of these. OK is a Best Linear
Unbiased Estimator (BLUE) method based on generalised linear regression. The OK
estimator is given by:

$$Z_{OK}(u) - m(u) = \sum_{\alpha=1}^{n(u)} \lambda_{\alpha}^{OK}(u)[Z(u_{\alpha}) - m(u_{\alpha})] \quad (2.3)$$

where $Z_{OK}(u)$ is the OK estimator at location $u$, $\lambda_{\alpha}^{OK}(u)$ is the kriging weight assigned to
sample value $z(u_{\alpha})$, $m(u)$ is the expected value of $Z(u)$, and $m(u_{\alpha})$ that of $Z(u_{\alpha})$.

Ordinary Kriging assumes that the mean $m(u)$ is constant, but unknown in the
local neighbourhood centred at the point being estimated. For OK the estimates are
chosen so as to minimise the error variance $\sigma^2_E(u)$ between the estimated values and the
true values. The estimation or error variance is given by:

$$\sigma^2_E(u) = Var[Z^*(u) - Z(u)]$$

To ensure that the unbiasedness condition $E[Z^*(u) - Z(u)] = 0$ is satisfied the
estimation variance is minimised under the constraint that the sum of the kriging weights
is one which also ensures that mean is filtered out of (2.3). The OK estimator is then:
\[ Z_{OK}^*(\mathbf{u}) = \sum_{\alpha=1}^{n(u)} \lambda_{\alpha}^{OK}(\mathbf{u})[Z(\mathbf{u}_\alpha)] \]

with
\[ \sum_{\alpha=1}^{n(u)} \lambda_{\alpha}^{OK}(\mathbf{u}) = 1 \]

The parameters determined from the semivariogram model are used to calculate the weights \( \lambda_{\alpha}^{OK}(\mathbf{u}) \). The weight parameters of the kriging equation at point \( \mathbf{u} \) are solved by using the covariances calculated from a chosen covariance function (our conceptual model) of all data points within the neighbourhood at point \( \mathbf{u} \). The system of equations to solve for the weights, called the OK system may be written as:

\[
\begin{bmatrix}
C(\mathbf{u}_1 - \mathbf{u}_1) & \cdots & C(\mathbf{u}_1 - \mathbf{u}_{\alpha(\mathbf{u})}) \\
\vdots & \ddots & \vdots \\
C(\mathbf{u}_{\alpha(\mathbf{u})} - \mathbf{u}_1) & \cdots & C(\mathbf{u}_{\alpha(\mathbf{u})} - \mathbf{u}_{\alpha(\mathbf{u})})
\end{bmatrix}
\begin{bmatrix}
\lambda_{1}^{OK}(\mathbf{u}) \\
\vdots \\
\lambda_{\alpha(\mathbf{u})}^{OK}(\mathbf{u})
\end{bmatrix}
= \begin{bmatrix}
C(\mathbf{u}_1 - \mathbf{u}_1) \\
\vdots \\
C(\mathbf{u}_{\alpha(\mathbf{u})} - \mathbf{u}_1)
\end{bmatrix}
\begin{bmatrix}
1 \\
\vdots \\
1
\end{bmatrix}
\]

where \( C(\mathbf{u}_i - \mathbf{u}_j) \) is the covariance between points \( \mathbf{u}_i \) and \( \mathbf{u}_j \) (the matrix is the covariance between all the sample points), \( \lambda_{\alpha}^{OK}(\mathbf{u}) \) is the OK weight at point \( \mathbf{u}_\alpha \), \( \mu_{OK}(\mathbf{u}) \) denotes the Lagrange multiplier and \( C(\mathbf{u}_i - \mathbf{u}) \) the covariance between point \( \mathbf{u}_i \) and the estimation point \( \mathbf{u} \).

### 2.4 Block Kriging

Up until now the discussion has referred to estimation of attribute values at a point or points using point sample data. In most mining applications the goal is to estimate the average value of attribute \( z \) over a block of certain dimensions, The estimate of the grade of a block can be obtained as the linear average of the point estimates (e.g. OK estimates) contained within it:

\[
z^*_V(\mathbf{u}) = \frac{1}{N} \sum_{i=1}^{N} z^*_V(\mathbf{u}_i) = \frac{1}{N} \sum_{i=1}^{N} \sum_{\alpha=1}^{n(\mathbf{u})} \lambda_{\alpha}^{OK}(\mathbf{u}_i) z(\mathbf{u}_\alpha)
\]

where \( z^*_V(\mathbf{u}) \) is the estimated block grade, \( z^*_V(\mathbf{u}_i) \) is the OK estimate at point \( \mathbf{u}_i \) and \( \lambda_{\alpha}^{OK}(\mathbf{u}_i) \) is the OK weight associated to the \( z \)-datum at location \( \mathbf{u}_i \).
This approach is computationally expensive and so in practice the block is estimated directly.

\[ Z_V(u) = \sum_{\alpha=1}^{n(u)} \lambda_{\alpha V}^{OK}(u)[Z(u_\alpha)] \]

where \( \lambda_{\alpha V}^{OK}(u) \) is the block kriging weight assigned to the datum \( z(u_\alpha) \). The block kriging weights can be shown to be the average of the \( N \) point kriging weights, provided the same sample points are used in the OK estimation of each of the block discretisation points. The block kriging system of equations to solve for these weights is similar to that given for the point kriging weights (equation 2-6). The only difference is that the right hand side term, the sample point to estimation point covariance, \( C(u_\alpha - u) \), is replaced by the sample point to estimation block covariance, \( \tilde{C}(u_\alpha, V(u)) \). The block covariance is approximated by the average of the point-to-point covariances of all discretisation points within the block. Thus when choosing the number of discretisation points within blocks it is important to choose sufficiently many so that by choosing more points the point-to-block covariance does not change significantly.

The slope of linear regression between the true block values \( Z_V \) and the block estimates \( Z_V^* \) is a useful indication of ordinary kriging estimate quality: The regression should be close to one (ideally it should be one). The true block values are not known however the mathematical theory in calculating the slope of regression is well known (Armstrong, 1998). The slope \( \rho \) of the linear regression of \( Z_V \) on \( Z_V^* \) is given by:

\[ \rho = \frac{\text{Cov}[Z_V, Z_V^*]}{(\text{Cov}[Z_V, Z_V^*] - \mu)} \]  

2.5 Krige’s Relation and the Dispersion Variance

Estimating a distribution of unknown block values is useful as a tool in assessing estimates (practical application of this theory is discussed in section 4.5). \textit{Krige’s Relation} is:

\[ \sigma^2(V|A) = \sigma^2(V|V) + \sigma^2(V|A) \]
where $\sigma^2(v|A)$ is the total variance (the variance of the points within the domain $A$); $\sigma^2(v|V)$ is the variance of points within the blocks and; $\sigma^2(V|A)$ is the variance of blocks within the domain $A$.

The variance of points within the domain can be modelled from the samples providing the samples are representative. The variance of points within the blocks or the Dispersion Variance is estimated from the experimental semivariogram model using the theoretical equation:

\[
\sigma^2(v|V) = \bar{\gamma}(V|V) + \bar{\gamma}(v|v)
\]

where $\bar{\gamma}(V|V)$ is the average semivariogram value for all points that lie within the blocks to be estimated and $\bar{\gamma}(v|v)$ is the average semivariogram value for all the points.

### 2.6 Change of Support Estimation

Change of support (volume) estimation is based on the assumption that shape of the distribution of grades does not change as the support changes. Once the variance of blocks within the domain is available this may then be used along with a model of the point distribution (based on the sample/composite distribution) to estimate the block distribution. It is important to note that this method does not provide an estimate of any particular specific block(s) grade and tonnes but rather the total grade and tonnes within the domain. It is a model of the block histogram based on the composite histogram.

\[
\text{Total Variance} = \text{Variance within blocks} + \text{Variance between blocks}
\]

- **Known from sample histogram**
- **Can be worked out using the semivariogram model and block size**
- **Unknown**

The model fitted to the point distribution can be ‘corrected’ to take account of different supports. The correction leaves the mean of the distribution unchanged and the variance is altered by a ‘real’ block correction factor or coefficient ($r$) to give the block
distribution. The real block correction factor is the ratio of the block variance to the point variance: \( r = 1 - \frac{\sigma^2(v|A)}{\sigma^2(v|V)} \). Three commonly used correction methods are: the Affine Correction; the Lognormal Correction; and the Discrete Gaussian Correction. Details about the first two methods may be found in Isaaks and Srivastava (1989) whilst the last method is discussed in detail in Rivoirard (1994). Further references are Chiles and Delfiner (1999) and Journel&Huijbregts (1981).

2.7 Indicator Kriging

Indicator kriging is a non-linear technique allowing one to estimate probabilities of exceeding pre-specified cut-offs without the smoothing effect of linear interpolation. With ordinary kriging estimates as applied in mining the estimate is made and then cut-offs are applied. Indicator kriging first defines cut-offs or thresholds and then estimates are made and as a result the smoothing effect may be partly avoided.

Indicator Kriging (IK) was introduced by Journel in 1983. It involves coding the data by thresholds or categories. The initial goal is to estimate the distribution of an attribute at each point where the value of the attribute is unknown. In doing so the uncertainty of each estimate location is modelled much more effectively than with the ordinary kriging variance which does not depend on data values but only on the covariance model used and the data locations.

IK is a non-parametric approach to the estimation of the distribution as it estimates the distribution at each unknown point without recourse to parameters or constraints. IK makes no assumptions concerning the shape of the distribution as determined by the indicators, but does make assumptions concerning the shape of the distribution between the indicators chosen as a model has to be chosen (usually linear) to interpolate between them.

In coding the data by indicators the spatial distribution of an attribute at different cut-offs, or within certain categories can be analysed e.g. large values in a study area may be less continuous than small values. The analysis occurs both visually, via the digital contouring of the data, and mathematically with the generation of experimental indicator semivariograms. IK allows analysis, at any location with unknown value, of probabilities computed from the prior distribution that the value is greater than or less than the thresholds used and/or within a category or not. The output from IK is a discretised
cumulative distribution function (cdf)) at each point. The number of classes on which the cdf is based corresponds to the number of K thresholds or categories used. Because the cdf depends on the prior distributions it is called a conditional cumulative distribution function (ccdf).

The start of the indicator approach is to code the samples into categories or thresholds. Critical values of the attribute e.g. ore/waste cut-offs should be made thresholds so that the ccdf value at this threshold will not have to be interpolated or extrapolated later. Generally more thresholds should be chosen within the part of the distribution that is of greatest interest but experimental indicator semivariograms at extreme thresholds may not be well defined if there are few pairs of data in these categories.

Each sample is coded with an indicator (normally 1 for Yes and 0 for No) to signify whether the sample falls into a category or not. The Isatis program used in this thesis defines the binary indicator data for \( k = 1, \ldots, K \) at a given location as:

\[
i(u; z_k) = \begin{cases} 
1 & \text{if } z(u_a) \geq z_k \\
0 & \text{otherwise}
\end{cases}
\]

The ccdf is modelled as the set of posterior probabilities of being less than a threshold for all the K thresholds/categories thus for \( k = 1, \ldots, K \):

\[
F(u; z_k|n) = \text{Prob}[Z(u) \leq z_k|n] = E[I(u; z_k)]
\]

where \((n)\) expresses conditioning to the local information for each threshold/category and \( z_k \) denotes the \( k \)th threshold of the continuous attribute \( z \). The function \( I(u; z_k) \) corresponds to the indicator random variable for \( z_k \) at location \( u \).

The IK process allows the analysis of risk or local uncertainty at each unknown point. The resulting estimates can be interpreted as either:

1. Probabilities:- The probability that the grade is above a specified threshold; or
2. Proportions–: The proportion of the block above the specified threshold – This will yield a volume estimate on this material which could, for example, be ore.

From the ccdf at a point estimates may be derived using different methods for post processing the indicator data.

The IK methodology of first assessing the local uncertainty and then generating estimates with this knowledge is more detailed than the SK or OK methodology which generating estimates without this knowledge.

Semivariogram models are created for each threshold. These semivariograms are computed by substituting indicator data $i(u_\alpha; z_k)$ for z-data $z(u_\alpha)$. The experimental indicator semivariogram is defined as:

$$ \gamma(h; u_\alpha) = \frac{2}{2N(h)} \sum_{\alpha=1}^N (i(u_\alpha; z_k) - i(u_\alpha + h; z_k))^2 $$

At each location where the attribute value is unknown the ccdf is derived using a kriging algorithm such as OK to krige the sample indicator values. The ccdf values for each indicator are the prior probabilities that the value belongs in each category.

### 2.7.1 Estimating ccdf Values via Ordinary Indicator Kriging

The ordinary Indicator Kriging (oIK) estimator is a linear combination of the indicators in the neighbourhood being estimated. Using oIK takes into account variations in the mean between neighbourhoods. The oIK estimator is OK applied to the assigned indicator set. The oIK estimator is given by:

$$ [F(u; z_k|n))]_{oIK} = \sum_{\alpha=1}^{n(u)} \lambda_{oIK}^\alpha(u; z_k) I(u_\alpha; z_k) $$

where the weights $\lambda_{oIK}^\alpha(u; z_k)$ sum to 1. The system of equations for deriving the weights is similar to the system in Equation 2-5 with the covariances now being between the indicators at each point.
It is important to note that kriging the indicators generates conditional probabilities only at the thresholds specified. These probability estimates must be post-processed in order to rebuild the local cumulative density function (cdf) for each grid node, in order to derive the tonnage and metal quantity for other cutoffs. It is then possible to calculate the probability for the variable to exceed any cutoff or to calculate the average value of the variable above or below this cutoff, accounting for a possible change of support.

The cdf values between thresholds are interpolated and beyond the smallest and largest cutoff they are extrapolated. It is usual (Goovaerts (1997)) for the interpolation between thresholds \( z_{k-1} \) and \( z_k \) to be done using a linear model by putting for each \( z \in (z_{k-1}, z_k) \).

\[
[F(z)]_{\text{Lin}} = F^*(z_{k-1}) + \left[ \frac{Z - z_{k-1}}{z_k - z_{k-1}} \right] \cdot [F^*(z_k) - F^*(z_{k-1})] \tag{2-14}
\]

For the ccdf values beyond the smallest and largest values two models that are commonly used are the Power cdf model (2-15) and the hyperbolic cdf model (2-16).

To extrapolate beyond the lowest threshold \( z_1 \) to a fixed minimum value \( z_{min} \) the power model is given by

\[
[F(z)]_{\text{Pow}} = \left[ \frac{Z - z_{min}}{z_1 - z_{min}} \right]^{\omega} \cdot F^*(z_1) \tag{2-15}
\]

for all \( z \in (z_{min}, z_1) \) where the exponent \( \omega \) is strictly positive. When \( \omega = 1 \) the power model is reduced to the linear model. When the lower tail is negatively skewed, a value of \( \omega > 1 \) is required, while for a positively skewed lower tail a value less than 1 is required.

For the upper tail extrapolation to a maximum value \( z_{max} \) beyond the highest threshold \( z_K \) the model is given by

\[
[F(z)]_{\text{Pow}} = F^*(z_K) + \left[ \frac{Z - z_K}{z_{max} - z_K} \right]^{\omega} \cdot [1 - F^*(z_K)]
\]

for all \( z \in (z_K, z_{max}) \). For a positively skewed upper tail a value of \( \omega < 1 \) is needed, while for a negatively skewed upper tail a value greater than 1 is required.

The hyperbolic model is used to extrapolate the upper tail of a positively skewed distribution. It is given by
for all $z \geq z_K$ with the parameter $\omega \geq 1$ controlling how fast the cdf model reaches its limiting value: A value of $\omega$ close to 1 corresponds to a long tail.

### 2.7.2 IK Block cdf values

In estimating IK block cdf values there needs to be a correction for the larger volume of the blocks compared to the smaller volume of the samples they are estimated from. This Volume Variance Correction (VVC) becomes an important issue in producing accurate estimates. The volume variance effect will be greater when data are uncorrelated (have more entropy), so the experimental indicator semivariograms provide a guide to assessing the impact of change of support. The variance of the blocks should be reduced to account for their having a larger volume. In OK this VVC is handled as part of the kriging equations.

It was noted in Section 2.4 that the estimate of the grade of a block in OK is the linear average of the point estimates. For oIK the indicator variable $i(u; z)$ is a non-linear transform of the original variable. Thus the block indicator $i_v(u; z)$ is not a linear average of the point indicators. The linear average of the point indicators produces a composite cdf which is the proportion of point values within the block that do not exceed the threshold value whereas the block cdf gives the probability that the average $z$-value of the whole block is no greater than $z$.

The average block indicator covariance is approximated by the average of point support covariance but this is now a composite and there is now no change of support inherent here as there is with OK. In other words through using the composited point support covariance the right hand side expression of the matrix of kriging equations has been populated and the weights for oIK determined, but no VVC has taken place.

The point support ccdfs are corrected for the larger volume of blocks by working out the variances of the block support ccdfs before or after compositing and then applying a correction algorithm such as the indirect lognormal correction, lognormal correction or affine correction. These corrections work by squashing the cdf at each block centroid. In this thesis the variances for block support are worked out after compositing and the correction algorithm applied was the affine method.
2.7.3 Deriving Estimates from the ccdf

The E-type estimate is the average grade of the block derived by calculating the weighted average grade of each block using all the thresholds of the ccdf and the associated probabilities of exceeding those thresholds. The expected value of the ccdf above any threshold is given by:

\[ z_E^*(u) = \int_{-\infty}^{+\infty} zdF(u; z|n) \approx \sum_{k=1}^{K+1} \bar{z}_k \left[ F(u; z_k|n) - F(u; z_{k-1}|n) \right] \]

The IK results also allow the estimate of the ccdf to be used to estimate the recoverable resource tonnes for the chosen SMU above or below a cut-off (in this thesis 60% Fe is the most relevant).
3 Section Seven Geology and Data Description

The aim of this chapter is to outline the data available and ensure that they are valid for further work. It is important that the data are understood and any strengths, weaknesses and assumptions are discussed. The chapter leads off with a description of the location and geology then moves on to introduce the data available and how the data were validated and tagged with geological grouping information. A small number of data was excluded from the study and these are set out in this chapter along with the reasons for excluding them. A description of how the 3 dimensional geology model of the hardcap was made is given next describing how the hardcap was divided into domains. The size and extent of the domains is shown.

3.1 Location

The Section Seven deposit is located 5 km west of Mt Tom Price mine, on the south eastern side of the Turner Syncline (see Figure 3-1). The mineralisation has a strike length of approximately 1.5 km in an East/West direction and is approximately 700 m wide (North/South) and extends to a maximum depth of approximately 140 m. Access to the mine is restricted to Rio Tinto personnel or approved and escorted visitors.

![Figure 3-1 Section Seven Location – The Turner Syncline geology in plan view forms a ‘ray-gun’ pattern pointing west.](image-url)
3.2 Geology

The Section Seven deposit is hosted within the Dales Gorge, Whaleback Shale and Joffre members of the Brockman Iron Formation. These stratigraphic divisions are shown in Figure 3-2. The deposit strata are gently open folds with an overall dip to the north and a shallow plunge to the west. This thesis is concerned only with a subset of the mineralisation specifically that within the hardcap zone.

Hardcap is part of what geologists describe as the regolith. The regolith is defined as the entire unconsolidated and secondary re-cemented cover that overlies more coherent bedrock. It may be formed by erosion of in-situ material or transport and deposition of material from elsewhere. The regolith includes many lithologies, for example, pisolites and detritals. In a similar way hardcap represents largely, but not exclusively, weathered in-situ rock, and one of its most common features is the conversion of hematite (Fe₂O₃) to various forms of goethite (Fe₂O₃.OH), indeed many geologists call hardcap the “hydrated zone” after this feature. A conceptual, deposit scale, model of hardcap is shown in Figure 3-3, the hardcap is flagged as HYD in this figure. Figure 3-3 does not show the local variations in lithologies that occur within the hardcap. Lithologies represented in hardcap other than weathered in-situ rock include cavities and cavity fill material such as small clay pods, siliceous zones, pisolite zones and BIF pods. There are also variations in all of the above caused by different degrees of weathering. It is a risk boundary for mining as material above this boundary is more variable in lithology and grade compared to material under the boundary.
Figure 3-2 Stratigraphic Column for the Hamersley Group
In terms of a concept for geological modelling the hardcap is a regional blanket on top of all bedded material and underneath any alluvial or colluvial material. The hardcap at Section 7 ranges from 5 m to 30 m thickness and extends over most of the deposit. As part of the work undertaken for this thesis a three dimensional model of the hardcap of Section 7 was created using Vulcan software. Interpretations from exploration drillholes were combined with bench mapping data and blasthole information from mining to create the model.

Mineralised hardcap blocks at Section 7 make up 25% of total blocks in the deposit as shown in Figure 3-4. The mineralised hardcap is separated into four domains by stratigraphy: 505, 435, 325 and 265 representing mineralised hardcap from the Footwall Zone, Dales Gorge, Whaleback Shale and Joffre Members. It can be seen from this figure that domain 505 contains very few samples and this domain was combined with the 435 domain which is adjacent to it stratigraphically (Figure 3-5 shows the domains in the block model in plan view).
3.3 Creating the Block Model

Drillholes intervals were flagged with domains using assays, gamma logs and geological logging data. Strings representing geological units were created on 60 m sections with some 30 m sections created where required. The strings were examined in section view in Vulcan whilst displaying the drillholes and other geological data. Adjustments were made to the strings to ensure that the interpretation fitted all the data. The interpretation was digitised along section lines as opposed to snapping to drillhole intercepts which can cause unrealistic 3D shapes when the strings are joined into wireframes. Conflicts in geological fact data between the different data sources were rare and when they did occur they were handled case-by-case. In general drillhole data were given priority over other geological data. The only cases when this did not occur were when the drillholes lacked downhole surveys.

Wireframes were created by linking the strings together and checks were completed to make sure that the wireframes matched the data. The block model was then created by flagging blocks with the appropriate wireframe to give each block a geological domain code. The block model was created in Vulcan using blocks sized at 30 m (X) × 30 m (Y) × 5 m (Z) this block size was half the drillhole spacing in the X and Y directions. The location of the origin of the model was sited so that most blocks had a drillhole at one outer corner which meant that the sample support for each block was similar. The total
The number of blocks was 3801, with 2631 in domain 505435 (104 were in domain 505 and 2,527 in domain 435), 485 in domain 325 and 685 in domain 265. The block model in plan view is shown in Figure 3-5 and this shows the blocks from the different domains with the largest and most continuous domain being 435.

![Figure 3-5 Block Model and Drillholes in Plan View (Dark Green 505, Green 435, Yellow 325, Blue 265)](image)

### 3.4 Data Description and Validation

The main data used to create the geological model and the only data used for grade interpolation were the exploration drillhole data, consisting of assays, geological logging and geophysics. The other set of data available are the data collected whilst mining the deposit specifically blast hole data and grade blocks.

#### 3.4.1 Exploration Data

The drillhole samples are located in space by the use of hole collar co-ordinates, sample depths and downhole surveys. No record of how drillholes were surveyed could be located, it is assumed that the drillhole coordinates in the database are accurate. The accuracy of downhole surveys for hardcap was not deemed to be of any consequence as deviations in the top 40m of any drillhole are minimal. No drill holes were excluded from use in estimation due to not having a downhole survey.

Seven holes from the 426 drillholes located at Section 7 were not used because they did not have a collar survey or were co-located with other drillholes. (Table 3-1.). In one instance the z-coordinate was missing.
A summary list of the number of holes used, the year they were drilled and the drilling method is shown in Table 3-2. From Table 3-2 it can be seen that there are two broad groups of holes, holes drilled pre-1999 and holes drilled from 1999 onwards. A plot of hole locations coloured by year drilled is shown in Figure 3-6.

### Table 3-2 Number of Drillholes, Drilling Method and Metres Drilled

<table>
<thead>
<tr>
<th>Year</th>
<th>Data</th>
<th>Diamond</th>
<th>Percussion</th>
<th>Reverse Circulation</th>
<th>Unknown</th>
<th>Grand Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>Holes</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Metres</td>
<td>798</td>
<td></td>
<td></td>
<td></td>
<td>798</td>
</tr>
<tr>
<td>1977</td>
<td>Holes</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
<td>38</td>
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<tr>
<td></td>
<td>Metres</td>
<td>3,588</td>
<td></td>
<td></td>
<td></td>
<td>3,588</td>
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<tr>
<td>1979</td>
<td>Holes</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Metres</td>
<td>1,836</td>
<td></td>
<td></td>
<td></td>
<td>1,836</td>
</tr>
<tr>
<td>1981</td>
<td>Holes</td>
<td>136</td>
<td></td>
<td>1</td>
<td>62</td>
<td>13,646</td>
</tr>
<tr>
<td></td>
<td>Metres</td>
<td>13,584</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1982</td>
<td>Holes</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Metres</td>
<td>171</td>
<td></td>
<td></td>
<td></td>
<td>171</td>
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<td>1986</td>
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<td></td>
<td></td>
<td>1</td>
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<td></td>
<td>24</td>
</tr>
<tr>
<td>1992</td>
<td>Holes</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Metres</td>
<td>204</td>
<td></td>
<td></td>
<td></td>
<td>204</td>
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<tr>
<td>1999</td>
<td>Holes</td>
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<td></td>
<td></td>
<td></td>
<td>1</td>
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<tr>
<td></td>
<td>Metres</td>
<td>376</td>
<td></td>
<td></td>
<td></td>
<td>376</td>
</tr>
<tr>
<td>2000</td>
<td>Holes</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>Metres</td>
<td>9,818</td>
<td></td>
<td></td>
<td></td>
<td>9,818</td>
</tr>
<tr>
<td>2005</td>
<td>Holes</td>
<td>39</td>
<td></td>
<td></td>
<td></td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Metres</td>
<td>2,136</td>
<td></td>
<td></td>
<td></td>
<td>2,136</td>
</tr>
<tr>
<td>2006</td>
<td>Holes</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Metres</td>
<td>187</td>
<td></td>
<td></td>
<td></td>
<td>187</td>
</tr>
<tr>
<td>Total Number of Holes</td>
<td>4</td>
<td>214</td>
<td>200</td>
<td>1</td>
<td>419</td>
<td></td>
</tr>
<tr>
<td>Total Metres</td>
<td>211</td>
<td>20,181</td>
<td>12,330</td>
<td>62</td>
<td>32,784</td>
<td></td>
</tr>
</tbody>
</table>
The samples used for assays and logging were collected in either 1.5 m or 2 m lengths and two dominant drilling methods were used. Prior to 1999 the drilling method was percussion hammer with the sample getting to the surface outside the drilling rods this method is referred to as open hole (OH) drilling and sampling. OH samples were taken from material drilled over a length of 1.5 m, there were 214 OH drillholes completed. From 1999 the sample was taken to the surface from the drill bit face through a tube inside the drilling rods this method is referred to as reverse circulation (RC) drilling. The RC samples were taken from material drilled over 2 m, there were 200 RC drillholes completed. RC drilling, in general, recovers a higher quality sample than OH drilling as it is less prone to any contamination. Only 4 holes were drilled by Diamond drilling.

Assays are available for the major attributes Fe, SiO$_2$, Al$_2$O$_3$ as well as for minor attributes P, Mn, LOI, S, TiO$_2$, MgO, CaO. Most samples are analysed for all these attributes and using this information and some assumptions about the mineralogy it is possible to estimate the whole rock analysis which should be very close to 100%. Any significant deviation can be used as an assay validation tool. There were four samples
whose assay values were altered to -99 as a flag to exclude them from the data used for further work on the basis that the total assay was too high. These are shown in Table 3-3 and this brought the total number of samples with no assays (signified by -99) to 15.

Table 3-3 Invalid Samples

<table>
<thead>
<tr>
<th>HOLE NAME</th>
<th>DEPTH_FROM (m)</th>
<th>DEPTH_TO (m)</th>
<th>TOTAL_ASSAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>R00SSEV114</td>
<td>0</td>
<td>2</td>
<td>105.18</td>
</tr>
<tr>
<td>R00SSEV114</td>
<td>2</td>
<td>4</td>
<td>106.99</td>
</tr>
<tr>
<td>R00SSEV127</td>
<td>0</td>
<td>2</td>
<td>105.74</td>
</tr>
<tr>
<td>R00SSEV127</td>
<td>2</td>
<td>4</td>
<td>104.06</td>
</tr>
</tbody>
</table>

There are 2947 samples coded 505, 435, 325, 265 and the total number of samples in each geozone split into pre-1999 and post-1999 categories is shown in Table 3-4.

Table 3-4 Numbers of Samples in Different Hardcap Domains

<table>
<thead>
<tr>
<th>Domain</th>
<th>Number of Samples</th>
<th>Number of Samples</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre 1999</td>
<td>Post 1999</td>
<td></td>
</tr>
<tr>
<td>265</td>
<td>537</td>
<td>298</td>
<td>239</td>
</tr>
<tr>
<td>325</td>
<td>327</td>
<td>210</td>
<td>117</td>
</tr>
<tr>
<td>435</td>
<td>2,007</td>
<td>1150</td>
<td>857</td>
</tr>
<tr>
<td>505</td>
<td>76</td>
<td>69</td>
<td>7</td>
</tr>
</tbody>
</table>

The most common sample length is 1.5 m (1,661 samples) and the next most common length is 2 m (1,217 samples). There are two 4 m samples with no assays, the remaining 67 samples are in intervals of less than 1 m and 64 of these samples are from one hole (67/786/86) the average of the 64 sample lengths is 0.10 m.

Box and whisker plots for Fe, SiO₂ and Al₂O₃ (Figure 3-7, Figure 3-8, Figure 3-9) show that with the exception of Fe in domain 505 there are outliers for each attribute. The three most extreme outliers for each attribute were examined further to check if these values were valid.
Figure 3-7 Boxplots of Fe by Domain

Figure 3-8 Boxplots of SiO₂ by Domain

Figure 3-9 Boxplots of Al₂O₃ by Domain
The lowest Fe and highest SiO₂ and Al₂O₃ values by domain are shown in Table 3-5.

<table>
<thead>
<tr>
<th>Domain</th>
<th>DHID</th>
<th>From</th>
<th>To</th>
<th>Fe</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>265</td>
<td>67/171</td>
<td>13.5</td>
<td>15</td>
<td>2.5</td>
<td>42.8</td>
<td>37.5</td>
</tr>
<tr>
<td>265</td>
<td>R00SSEV071</td>
<td>18</td>
<td>20</td>
<td>3.35</td>
<td>45.63</td>
<td>32.81</td>
</tr>
<tr>
<td>325</td>
<td>R00SSEV026</td>
<td>8</td>
<td>10</td>
<td>4.8</td>
<td>41.72</td>
<td>34.81</td>
</tr>
<tr>
<td>435</td>
<td>67/424</td>
<td>10.5</td>
<td>12</td>
<td>63.9</td>
<td>18.9</td>
<td>3.95</td>
</tr>
<tr>
<td>435</td>
<td>67/413</td>
<td>33</td>
<td>34.5</td>
<td>62.3</td>
<td>7.9</td>
<td>15.2</td>
</tr>
<tr>
<td>435</td>
<td>RC05SSEV052</td>
<td>22</td>
<td>24</td>
<td>52.86</td>
<td>24.28</td>
<td>4.68</td>
</tr>
<tr>
<td>265</td>
<td>67/171</td>
<td>13.5</td>
<td>15</td>
<td>37.5</td>
<td>2.5</td>
<td>42.8</td>
</tr>
<tr>
<td>325</td>
<td>R00SSEV026</td>
<td>8</td>
<td>10</td>
<td>34.81</td>
<td>4.8</td>
<td>41.72</td>
</tr>
</tbody>
</table>

The location of these samples relative to the rest of the samples in each of these holes was examined and it could be seen that these samples are outliers representing different lithologies in the hardcap domain, so they were retained. The total assay values of these samples are within limits and so these samples were left in the data set.

### 3.4.2 Comparison of Samples taken using Different Methods

It is necessary to check for any bias in assay results that could be due to the different sampling methods and/or sample lengths for the RC and OH methods, and check if it is reasonable to pool and use the data or if any data should be excluded. In order to investigate this sample statistics of the two different populations were calculated these are shown in Table 3-6, Table 3-7 and Table 3-8. Q-Q plots of the data were also generated and the Fe plot is shown in Figure 3-10 (Q-Q plots for the other attributes are shown in Appendix 1). Most samples are in the domains 435 and 265 so examination of these domains should give an idea of the reliability of samples from the different drilling methods.

<table>
<thead>
<tr>
<th>Geozone</th>
<th>Pre1999</th>
<th>NFe</th>
<th>NMissingFe</th>
<th>MeanFe</th>
<th>StDevFe</th>
<th>RangeFe</th>
</tr>
</thead>
<tbody>
<tr>
<td>265</td>
<td>n</td>
<td>236</td>
<td>3</td>
<td>54.83</td>
<td>8.59</td>
<td>61.08</td>
</tr>
<tr>
<td>265</td>
<td>y</td>
<td>295</td>
<td>3</td>
<td>55.70</td>
<td>7.18</td>
<td>61.5</td>
</tr>
<tr>
<td>325</td>
<td>n</td>
<td>115</td>
<td>2</td>
<td>49.03</td>
<td>11.89</td>
<td>59.42</td>
</tr>
<tr>
<td>325</td>
<td>y</td>
<td>210</td>
<td>0</td>
<td>48.96</td>
<td>8.69</td>
<td>53.9</td>
</tr>
<tr>
<td>435</td>
<td>n</td>
<td>857</td>
<td>0</td>
<td>56.52</td>
<td>6.72</td>
<td>50.78</td>
</tr>
<tr>
<td>435</td>
<td>y</td>
<td>1143</td>
<td>7</td>
<td>55.68</td>
<td>7.18</td>
<td>58</td>
</tr>
<tr>
<td>505</td>
<td>n</td>
<td>7</td>
<td>0</td>
<td>55.70</td>
<td>3.37</td>
<td>10.77</td>
</tr>
<tr>
<td>505</td>
<td>y</td>
<td>69</td>
<td>0</td>
<td>54.73</td>
<td>3.81</td>
<td>16.6</td>
</tr>
</tbody>
</table>
Table 3-7 SiO₂ Statistics of Samples Pre 1999 and 1999 onwards

<table>
<thead>
<tr>
<th>Geozone</th>
<th>Pre1999</th>
<th>NSiO₂</th>
<th>NMissingSiO₂</th>
<th>Mean SiO₂</th>
<th>StDev SiO₂</th>
<th>Range SiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>265</td>
<td>n</td>
<td>236</td>
<td>3</td>
<td>10.59</td>
<td>7.75</td>
<td>43.77</td>
</tr>
<tr>
<td>265</td>
<td>y</td>
<td>295</td>
<td>3</td>
<td>9.28</td>
<td>5.51</td>
<td>41.25</td>
</tr>
<tr>
<td>325</td>
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<td>115</td>
<td>2</td>
<td>12.12</td>
<td>10.13</td>
<td>41.07</td>
</tr>
<tr>
<td>325</td>
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<td>11.18</td>
<td>7.67</td>
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</tr>
<tr>
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<td>0</td>
<td>8.50</td>
<td>6.35</td>
<td>51.61</td>
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<td>1143</td>
<td>7</td>
<td>8.37</td>
<td>6.73</td>
<td>62.8</td>
</tr>
<tr>
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<td>n</td>
<td>7</td>
<td>0</td>
<td>7.76</td>
<td>3.75</td>
<td>12.28</td>
</tr>
<tr>
<td>505</td>
<td>y</td>
<td>69</td>
<td>0</td>
<td>8.91</td>
<td>4.05</td>
<td>20.88</td>
</tr>
</tbody>
</table>

Table 3-8 Al₂O₃ Statistics of Samples Pre 1999 and 1999 onwards

<table>
<thead>
<tr>
<th>Domain</th>
<th>Pre1999</th>
<th>NAi₂O₃</th>
<th>NMissing Al₂O₃</th>
<th>Mean Al₂O₃</th>
<th>StDev Al₂O₃</th>
<th>Range Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>265</td>
<td>n</td>
<td>236</td>
<td>3</td>
<td>3.81</td>
<td>3.75</td>
<td>32.04</td>
</tr>
<tr>
<td>265</td>
<td>y</td>
<td>295</td>
<td>3</td>
<td>3.69</td>
<td>3.82</td>
<td>36.87</td>
</tr>
<tr>
<td>325</td>
<td>n</td>
<td>115</td>
<td>2</td>
<td>7.12</td>
<td>6.63</td>
<td>34.06</td>
</tr>
<tr>
<td>325</td>
<td>y</td>
<td>210</td>
<td>0</td>
<td>7.39</td>
<td>4.75</td>
<td>27.68</td>
</tr>
<tr>
<td>435</td>
<td>n</td>
<td>857</td>
<td>0</td>
<td>3.00</td>
<td>2.73</td>
<td>27.84</td>
</tr>
<tr>
<td>435</td>
<td>y</td>
<td>1143</td>
<td>7</td>
<td>3.52</td>
<td>3.34</td>
<td>33.49</td>
</tr>
<tr>
<td>505</td>
<td>n</td>
<td>7</td>
<td>0</td>
<td>3.65</td>
<td>1.33</td>
<td>3.71</td>
</tr>
<tr>
<td>505</td>
<td>y</td>
<td>69</td>
<td>0</td>
<td>3.96</td>
<td>1.84</td>
<td>8.80</td>
</tr>
</tbody>
</table>

For domain 435 the mean of Fe for pre-1999 samples is slightly lower the silica slightly lower and Al₂O₃ slightly higher. For most domains where the mean of Fe is lower it would be expected that the means of silica and alumina be higher as is the case for the domain 265, however with slight differences and the mineralogy of hardcap these results are reasonable. It can be concluded that it is reasonable to pool the data and no data should be excluded for the reason of different lengths or sampling methods.

Figure 3-10 QQ Plots: Fe Open Hole Vs Reverse Circulation Samples for Domains 265, 325, 505

3.4.3 Blasthole data and Grade Blocks
Mine operations have been ongoing at Section 7 since 2001. Mining occurs on a 10 m bench and each blast is blocked out into grade blocks depending on a visual assessment of blasthole grades. The grade blocks represent the effective truth as they are the final information used to determine whether material is ore or not so they were used in this thesis as reconciliation data to compare the estimates to. Blastholes are approximately 7 m apart, 300 mm in diameter and drilled to approximately 10 m. The samples are taken from the cone of cuttings that collect around each blasthole using a shovel.

Grade blocks are created for waste (W), Low Grade (LG) and High Grade (HG). For each attribute the average value of the blasthole assays within each grade block provides the value for the grade block. Grade blocks are designed with vertical boundaries and most are 10 m high which was the mining bench height. A typical grade block is shown in Figure 3-11 the average grade of this block is 61.4% Fe each cross in the figure represents a blasthole location.

The grade blocks were proportioned into domains using domains assigned to model blocks. As an example, if a HG block was 50% from domain 505435, 30% from domain 325, and 20% from a non-hardcap domain then the tonnes from this block would be proportioned accordingly. The total HG within each domain provides the reconciliation data.
3.5 **Conclusions from Geology and Data Description**

This chapter has presented all the data available for analysis and possible use in estimating Fe SiO$_2$ and Al$_2$O$_3$ for the Section 7 Deposit. The creation of the 3D block model domains without grades has also been discussed.

In total, of the 426 drill holes available for the Section 7 Deposit, 419 were used and seven were excluded. The total number of samples available from these 419 holes for the hardcap domains was 2,951. Four of these samples were deemed invalid as their total assay was too high. Of the remaining 2,947 samples 15 had no assay values but still had valuable domain coding information and so these were used in creation of the geological model but not in estimating grades into the blocks. There are very few sample data available for the domain 505 so this will be pooled and used together with the domain 435, hereafter the combined domain shall be called 505435. The samples were collected by two different drilling techniques; approximately half the samples by each method. The samples were grouped by these methods and analysed for any bias. It was determined that there was no bias that would justify excluding any of the data.

The block model was created using geological data. The total amount of hardcap present in the deposit is 34% of the total volume of mineralisation. Three hardcap domains matching the samples were defined in order that these could be estimated separately.
4 Exploratory Data Analysis

This chapter deals with exploratory data analysis of the composited samples; it is from the composites that the estimates are made. In order to understand and choose the best parameters for estimation as well as understand the results of estimation it is necessary to understand:

- How the composites were created;
- The location of the composites relative to the blocks they shall be used to estimate;
- The statistical distribution of each attribute by domain and the correlation between the attributes;
- The spatial continuity of attributes.

The method by which the composites were created will be discussed. The exploratory data analysis and spatial continuity of the attributes Fe, SiO₂ and Al₂O₃ will also be discussed.

In order to prepare for Indicator Kriging the thresholds for each attribute will be chosen. The experimental semivariograms and semivariogram models for both ordinary kriging and indicator kriging will be generated for each domain. This is all necessary preparation for estimation which shall be discussed in Chapters 5 and 6.

4.1 Composite Creation

It is not possible to weight the samples by length in kriging because kriging systems have to specify the variogram based on samples that must be on standard lengths. The composite length chosen was 5 m, this length being a multiple of the 10 m bench height for mining. Composites were created in Vulcan using the ‘run length’ option with composites not allowed to cross domain boundaries, this method results in some composites created being less than 5m. Two examples of these can be seen in Figure 4-1, the two drill holes that can be seen on the figure are 67/73 and 67/419, also shown is the wireframe representing the base of the hardcap for domain 505435. The two sub 5 m length composites can be seen just above this wireframe, for drill hole 67/73 the length
that has resulted is 3.5 m and for 67/419 the length is 1.5 m. The total number of composites created for each domain and the number than 5 m is shown in Table 4-1.

Table 4-1 Composites created and number of composites <5 m

<table>
<thead>
<tr>
<th>Domain</th>
<th>Total Composites</th>
<th>Composites Under 5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>505435</td>
<td>786</td>
<td>188</td>
</tr>
<tr>
<td>325</td>
<td>125</td>
<td>37</td>
</tr>
<tr>
<td>265</td>
<td>206</td>
<td>56</td>
</tr>
</tbody>
</table>

The data were examined in order to determine if any composites should be omitted on the basis that they may bias the results if they are kept and treated as if they were 5 m long. The remaining composites will be kept treated as if they are of the same length.

Figure 4-1 Composite Lengths cut to Domain Boundaries

In order to determine what length of composites should be excluded (if any) the length weighted means of all the composites were compared to the means of composites groups (not weighted for length) formed by excluding lengths of less than lengths of 4.5, 4, 3.5, 3, 2.5, 2, 1.5, 1, 0.5 metres. The results of this analysis are shown in Figure 4-2, Figure 4-3, and Figure 4-4. The grade difference shown is the difference between the weighted mean of all the composites and the non–weighted mean of the composites with
length exclusions specified. From these figures it can be seen firstly that keeping all the composites will bias the mean lower for Fe (and higher for SiO₂ and Al₂O₃) in the 505435 and 325 domains with the reverse situation for the 265 domain. A choice to exclude samples that have less than 2m composite length produces little difference in the mean from the weighted composites and very few residuals are unused so this length was chosen as the minimum sample length to use for all domains. The number of composites excluded was 49 for domain 505435, 8 for domain 325 and 13 for domain 265.
4.2 Location of Composites and Blocks for Each Domain

In order to better understand which blocks may rely on fewer composites than others, and thus have less reliable estimates, a plot of the blocks and composites for all domains was completed (Figure 4-5). In this figure the dots represent the composites and the domain blocks are shown in a lighter shade of the composite colour. It was concluded that blocks in the Northeast of all domains have fewer composites to make use of in estimation. There are also some blocks in the southwest of domain 325 that have fewer composites to make use of.
4.3 Summary Statistics and Histograms of Composites

Summary statistics for the composites greater than or equal to 2.0 m in length are shown in Table 4-2. Domain 505435 has the highest mean Fe grade and lowest mean SiO₂ and Al₂O₃ grades. The coefficient of variation for Fe is relatively low compared with the other attributes across all domains indicating the lower variability of this attribute compared to SiO₂ and Al₂O₃. This suggests that the Fe estimates should be more accurate than estimates of the other attributes. The distribution of Fe is negatively skewed whereas those of SiO₂ and Al₂O₃ are positively skewed. This aspect may also be seen in the histograms shown in Figure 4-6.

<table>
<thead>
<tr>
<th>Domain</th>
<th>VAR</th>
<th>Count</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Var</th>
<th>CV</th>
<th>Skew</th>
<th>Kurt</th>
</tr>
</thead>
<tbody>
<tr>
<td>505435</td>
<td>Iron</td>
<td>727</td>
<td>22.29</td>
<td>64.54</td>
<td>55.9</td>
<td>29.2</td>
<td>0.1</td>
<td>-1.57</td>
<td>7.21</td>
</tr>
<tr>
<td>505435</td>
<td>Silica</td>
<td>727</td>
<td>1.29</td>
<td>52.4</td>
<td>8.59</td>
<td>27.88</td>
<td>0.61</td>
<td>2.17</td>
<td>11.8</td>
</tr>
<tr>
<td>505435</td>
<td>Alumina</td>
<td>727</td>
<td>0.43</td>
<td>16.57</td>
<td>3.32</td>
<td>5.4</td>
<td>0.7</td>
<td>2.29</td>
<td>10.63</td>
</tr>
<tr>
<td>325</td>
<td>Iron</td>
<td>117</td>
<td>9.56</td>
<td>60.71</td>
<td>49.11</td>
<td>69.84</td>
<td>0.17</td>
<td>-1.53</td>
<td>6.6</td>
</tr>
<tr>
<td>325</td>
<td>Silica</td>
<td>117</td>
<td>1.64</td>
<td>40.92</td>
<td>11.45</td>
<td>57.78</td>
<td>0.66</td>
<td>1.21</td>
<td>4.37</td>
</tr>
<tr>
<td>325</td>
<td>Alumina</td>
<td>117</td>
<td>2.37</td>
<td>30.33</td>
<td>7.2</td>
<td>21.52</td>
<td>0.64</td>
<td>2.14</td>
<td>8.51</td>
</tr>
<tr>
<td>265</td>
<td>Iron</td>
<td>196</td>
<td>18.92</td>
<td>63.17</td>
<td>55.32</td>
<td>50.97</td>
<td>0.13</td>
<td>-2.91</td>
<td>13.18</td>
</tr>
<tr>
<td>265</td>
<td>Silica</td>
<td>196</td>
<td>2.07</td>
<td>41.6</td>
<td>9.96</td>
<td>37.04</td>
<td>0.61</td>
<td>2.39</td>
<td>10.3</td>
</tr>
<tr>
<td>265</td>
<td>Alumina</td>
<td>196</td>
<td>0.96</td>
<td>26.25</td>
<td>3.71</td>
<td>10.9</td>
<td>0.89</td>
<td>3.91</td>
<td>22.26</td>
</tr>
</tbody>
</table>
The correlation coefficient for each attribute against the other attributes is shown in Table 4-3. Fe and SiO₂ and Fe and Al₂O₃ are highly correlated and SiO₂ and Al₂O₃ show correlation across all domains as well.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Fe-SiO₂</th>
<th>Fe-Al₂O₃</th>
<th>SiO₂-Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>505435</td>
<td>-0.85</td>
<td>-0.81</td>
<td>0.49</td>
</tr>
<tr>
<td>265</td>
<td>-0.93</td>
<td>-0.89</td>
<td>0.71</td>
</tr>
<tr>
<td>325</td>
<td>-0.88</td>
<td>-0.87</td>
<td>0.59</td>
</tr>
</tbody>
</table>

### 4.4 Indicator Kriging Thresholds

There were some important thresholds that needed to be used as they are important for processing and these were 50% Fe, 55% Fe and 60% Fe as well as 2.5% Al₂O₃ and 3.00% Al₂O₃. More thresholds were used for domain 505435 than for the other domains as the other domains did not have many composites. For domain 505435 11 thresholds were calculated based on percentages of the composite data. They were slightly modified in some instances to ensure the important cut-off grades were specified.
The thresholds are shown in Table 4-4 and instances where they were modified are shown in blue.

<table>
<thead>
<tr>
<th>Quantile</th>
<th>Fe</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>46.04</td>
<td>2.73</td>
<td>0.96</td>
</tr>
<tr>
<td>0.1</td>
<td>49.34</td>
<td>50.00</td>
<td>1.22</td>
</tr>
<tr>
<td>0.2</td>
<td>52.31</td>
<td>4.83</td>
<td>1.68</td>
</tr>
<tr>
<td>0.3</td>
<td>54.50</td>
<td>55.00</td>
<td>2.00</td>
</tr>
<tr>
<td>0.4</td>
<td>55.65</td>
<td>6.4</td>
<td>2.36</td>
</tr>
<tr>
<td>0.5</td>
<td>56.80</td>
<td>7.28</td>
<td>2.76</td>
</tr>
<tr>
<td>0.6</td>
<td>57.85</td>
<td>8.25</td>
<td>3.21</td>
</tr>
<tr>
<td>0.7</td>
<td>59.03</td>
<td>9.71</td>
<td>3.71</td>
</tr>
<tr>
<td>0.8</td>
<td>60.19</td>
<td>60.00</td>
<td>4.5</td>
</tr>
<tr>
<td>0.9</td>
<td>61.51</td>
<td>15.19</td>
<td>6.03</td>
</tr>
<tr>
<td>0.95</td>
<td>62.47</td>
<td>18.82</td>
<td>7.65</td>
</tr>
</tbody>
</table>

Thresholds for the 325 and 265 domains were calculated and the quantiles and corresponding values are shown in Table 4-5 and Table 4-6. Thresholds were slightly modified in some instances to ensure the important threshold grades were used (shown in blue).

<table>
<thead>
<tr>
<th>Quantile</th>
<th>Fe</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>47.03</td>
<td>2.51</td>
<td>2.68</td>
</tr>
<tr>
<td>0.5</td>
<td>50.97</td>
<td>50.00</td>
<td>3.01</td>
</tr>
<tr>
<td>0.8</td>
<td>55.41</td>
<td>55.00</td>
<td>4.2</td>
</tr>
<tr>
<td>0.9</td>
<td>58.23</td>
<td>9.41</td>
<td>5.85</td>
</tr>
<tr>
<td>0.95</td>
<td>59.28</td>
<td>60.00</td>
<td>7.43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantile</th>
<th>Fe</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>49.38</td>
<td>50.00</td>
<td>1.77</td>
</tr>
<tr>
<td>0.3</td>
<td>55.15</td>
<td>55.00</td>
<td>2.52</td>
</tr>
<tr>
<td>0.5</td>
<td>57.06</td>
<td>8.63</td>
<td>2.89</td>
</tr>
<tr>
<td>0.6</td>
<td>58.16</td>
<td>10.61</td>
<td>3.62</td>
</tr>
<tr>
<td>0.8</td>
<td>59.63</td>
<td>60.00</td>
<td>6.52</td>
</tr>
</tbody>
</table>

Using the thresholds above each datum was coded with a one or zero depending on whether it was above or below the threshold: zero if below and one otherwise.

4.5 Continuity

In order to examine the composites for any directions of continuity semivariogram maps were generated for all domains. The composite data semivariogram maps for all attributes of domain 505435 are shown in Figure 4-7. The maps for all attributes of the other domains are contained in Appendix 1.
The maps for domain 505435 show weak anisotropy in the XY Plane with a direction of maximum continuity possibly being defined in the direction 110° for Fe and SiO₂ but no direction of maximum continuity apparent for Al₂O₃. On this basis omnidirectional experimental semivariograms for this domain were calculated in the XY Plane with anisotropy modelled in the Z direction only. The maps for domains 325 and 265 show no preferred direction of continuity so these were treated similarly.

The parameters used to generate the experimental semivariograms are also shown in Appendix 1. The number of structures used to model the semivariogram was kept constant, two structures in addition to the nugget were found to be sufficient. The omnidirectional experimental semivariograms and corresponding isotropic semivariogram models are shown in Figure 4-8, Figure 4-9, and Figure 4-10. Models of the different attributes within the same domain were deliberately created to be similar as the data supported this and there are also strong correlations between the attributes that were wished to be preserved in the estimates.

The percentage nugget modelled for domain 505435 was approximately 30% of the composite variance, for domain 325 approximately 50%, and for domain 265 approximately 10%. The ranges of the last structure for the different domains are shown in Table 4-7. It should also be noted that the short range (70 m) structures (nugget + 1st structure) of domain 505435 makes up 80% of the composite variance for this domain.

<table>
<thead>
<tr>
<th>Domain</th>
<th>X/Y Plane</th>
<th>Z Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>505435</td>
<td>160 m</td>
<td>16 m</td>
</tr>
<tr>
<td>325</td>
<td>180 m</td>
<td>16 m</td>
</tr>
<tr>
<td>265</td>
<td>90 m</td>
<td>24 m</td>
</tr>
</tbody>
</table>
Figure 4-7 505435 Semivariogram Maps for Attributes
Figure 4-8 Semivariogram Models and Parameters for Domain 505435
**Figure 4-9 Semivariogram Models and Parameters for Domain 325**

**Isatis**

**Comps/Lines (Sel: 325)**
- **Variable #1:** FE
- **Experimental Variogram:** in 1 direction(s)
  - **Directional Scales:** (90.00m, 90.00m, 16.00m)
  - **Model:** 3 basic structure(s)
    - **S1:** Nugget effect, Sill = 35.1
    - **S2:** Spherical - Range = 16.00m, Sill = 12.1
    - **S3:** Spherical - Range = 16.00m, Sill = 16.00m

**Isatis**

**Comps/Lines (Sel: 325)**
- **Variable #1:** SIO2
- **Experimental Variogram:** in 1 direction(s)
  - **Directional Scales:** (90.00m, 90.00m, 16.00m)
  - **Model:** 3 basic structure(s)
    - **S1:** Nugget effect, Sill = 29
    - **S2:** Spherical - Range = 16.00m, Sill = 10
    - **S3:** Spherical - Range = 16.00m, Sill = 18.5

**Isatis**

**Comps/Lines (Sel: 325)**
- **Variable #1:** AL2O3
- **Experimental Variogram:** in 1 direction(s)
  - **Directional Scales:** (90.00m, 90.00m, 16.00m)
  - **Model:** 3 basic structure(s)
    - **S1:** Nugget effect, Sill = 10.87
    - **S2:** Spherical - Range = 16.00m, Sill = 3.75
    - **S3:** Spherical - Range = 16.00m, Sill = 6.94
Figure 4-10 Semivariogram Models and Parameters for Domain 265
4.6 Indicator Variable Continuity

Semivariogram maps for domain 505435 showed the slight anisotropy seen in direction 110° for the full composite in the first seven thresholds. Experimental semivariograms for these thresholds were generated and modelled using this anisotropy. The remaining four experimental semivariograms were generated and modelled as isotropic in the XY plane. The indicator semivariogram maps for domains 325 and 265 indicate no anisotropy in the XY plane and so these were modelled as isotropic in this plane.

The indicator semivariogram maps are shown in Appendix 2 and indicator models for all domains, thresholds and attributes, are shown in Appendix 3. Summaries of the semivariogram model parameters are shown in Figure 4-11 to Figure 4-16. Nuggets for attributes varied from 17 to 53 percent of the sill for domain 505435, and 54 to 90 percent of the sill for domain 325. For domain 265 nuggets were consistently 33 percent of the sill. Ranges for attributes in the direction of maximum continuity varied from 140 m to 360 m for domain 505435, 70 m to 200 m for domain 325, and 70 m to 300 m for domain 265.

![Domain 505435 Indicator Modelled Nuggets and Structures (Fe)](image)

Nugget Value (%)  1st Structure Value (%)  2nd Structure Value (%)

Figure 4-11 Domain 505435 Nugget and Structure Values
Figure 4-12 Domain 505435 Ranges of Models for Indicators

Figure 4-13 Domain 325 Nugget and Structure Variance Values
Figure 4-14 Domain 325 Ranges of Models for Indicators

Figure 4-15 Domain 265 Nugget and Structure Variance Values
Conclusions from Exploratory Data Analysis

Composites were created from the samples in 5 m length with some lengths less than this created at domain boundaries. Lengths less than 2 m were excluded from further processing as they would slightly bias the results, the exclusions represented approximately 6% of the composites. The composites available represent the domains that they shall be used to estimate reasonably well.

Statistical analysis of the composite data showed there were no attributes with a CV greater than one and from this it was concluded that there were no extreme values in the data with a significant impact on the estimation of block grades. There are strong correlations between the attributes to be estimated for all domains.

Semivariogram models of the data in the XY plane are isotropic. Typical ranges are 160 m for domain 505435, 180 m for domain 325, and 90 m for domain 265. Ranges of continuity in the Z direction were 16-24 m. Continuity analysis of indicator variables for the 505435 domain show weak anisotropy for the first seven thresholds (quantiles 0.05 to 0.6 inclusive) and no anisotropy for the last four thresholds. No anisotropy is shown for the other domains. Ranges of continuity for indicator thresholds in the direction of maximum continuity varied from 140 m to 360 m for domain 505435, 70 m to 200 m for domain 325, and 70 m to 300 m for domain 265.
5 Estimation

This chapter is about the process of estimation, it sets out how ordinary kriging, change of support and indicator kriging were carried out. All these methods require that parameters be selected and there is discussion on which parameters were selected and the way in which they were selected. Firstly the selection of search neighbourhood and estimation parameters for ordinary kriging and indicator kriging are described. The rest of the chapter steps through the parameters chosen for the estimation methods in order of Ordinary Kriging, Global Change of Support and Indicator Kriging.

5.1 Block and SMU sizes

The block size of the geology models built for estimation was 30 m × 30 m × 5 m and the OK and GCoS estimates will use this block size for estimation. The IK method allows for the choice of SMU’s that are smaller than this and a realistic SMU is 15 m × 15 m × 5 m. The IK estimates will use the same 30 m × 30 m × 5 m block but a 15 m × 15 m × 5 m SMU size within these blocks.

5.2 Search Neighbourhood Selection

Search neighbourhoods used in this thesis were chosen taking into consideration the end uses for the estimates, quantitative criteria, and geology (relevance of nearby samples). The estimates generated in this thesis would be for estimating the overall resource tonnes and grades as well as for mine planning. The latter meant that the accuracy of estimates locally was important as they would be used for scheduling mining. Criteria for assessing the search neighbourhoods by Quantitative Kriging Neighbourhood Analysis (QKNA) were discussed in the Literature Review (Section 1.3). The geology of Hardcap was discussed in the Section 3.2 and it may be concluded from this that the relevance of nearby samples may not be high due to the high variability of lithology and weathering over short distances.

QKNA was run for all domains and the criteria used to assess the results incorporated the percentage of blocks filled for each run. Twelve search neighbourhoods were tested for domain 505435. The neighbourhoods tested and results are shown in Table 5-1 and the final search sizes are shown highlighted. The minimum number of composites used was varied as shown. The mean slope of regression results show little variance with lower results related to lower minimum number of samples. For all tests the mean slope of regression exceeded 0.78.
The percentage of negative weights was quite low (never more than 3.5%) and only varied significantly when the search height radius was dropped to 8 m. The results also show the percentage of blocks estimated and variations in z dimension of the search for smaller x/y dimension searches did produce significantly lower amounts of blocks estimated. For example the 90 m (X) × 90 m (Y) × 32 m (Z) search with a minimum number of samples of 8 estimated 80% of blocks whereas a 90 m (X) × 90 m (Y) × 50 m (Z) search with the same number of samples estimated 90% of blocks. This is caused by topography interacting with the search.

Based on these results and considering the other important factors discussed previously a two pass search strategy was selected for domain 505435; two passes being needed as the first pass would not estimate all the blocks. The first pass was selected to be 90 m × 90 m × 50 m and this would estimate 90% of the blocks and the second pass to estimate the remaining blocks was 180 m × 180 m × 100 m.

Similar search size tests were completed for the other domains and these are shown in Appendix 4. Due to the smaller number of composites available for domains 325 and 265 the number of composites tested for estimation was lowered to 8, 4 and 2. It was possible to estimate both these domains using a minimum of 8 composites and search sizes were determined from the results to be 180 m × 180 m × 50 m and 360 m × 360 m × 100 m for the first pass and second pass respectively. The slope of regression results for domain 325 are lower than the other domains because there are fewer samples available to use in estimation. The search sizes and other kriging parameters used for each domain are summarised in Table 5-2.
<table>
<thead>
<tr>
<th>Run Number (Search radius in metres X x Y x Z)</th>
<th>Minimum Number of Samples</th>
<th>Slope Z/Z* Mean</th>
<th>% Blocks Filled</th>
<th>Negative weights Mean</th>
<th>Weight of mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1 90 × 90 × 16</td>
<td>4</td>
<td>0.78</td>
<td>99.81%</td>
<td>-0.3%</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.83</td>
<td>99.51%</td>
<td>-0.3%</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.88</td>
<td>99.01%</td>
<td>-0.4%</td>
<td>0.21</td>
</tr>
<tr>
<td>Run 2 90 × 90 × 32</td>
<td>4</td>
<td>0.78</td>
<td>94.98%</td>
<td>-0.7%</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.82</td>
<td>79.63%</td>
<td>-0.8%</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.85</td>
<td>57.85%</td>
<td>-0.9%</td>
<td>0.27</td>
</tr>
<tr>
<td>Run 3 90 × 90 × 50</td>
<td>4</td>
<td>0.79</td>
<td>98.10%</td>
<td>-0.8%</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.81</td>
<td>90.46%</td>
<td>-0.8%</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.84</td>
<td>78.49%</td>
<td>-1.0%</td>
<td>0.29</td>
</tr>
<tr>
<td>Run 4 180 × 180 × 8</td>
<td>4</td>
<td>0.81</td>
<td>97.99%</td>
<td>-0.1%</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.85</td>
<td>87.95%</td>
<td>-0.1%</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.88</td>
<td>74.31%</td>
<td>-0.2%</td>
<td>0.25</td>
</tr>
<tr>
<td>Run 5 180 × 180 × 16</td>
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<td>0.84</td>
<td>99.73%</td>
<td>-1.6%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.85</td>
<td>97.34%</td>
<td>-1.6%</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.86</td>
<td>92.70%</td>
<td>-1.7%</td>
<td>0.32</td>
</tr>
<tr>
<td>Run 6 180 × 180 × 32</td>
<td>4</td>
<td>0.86</td>
<td>99.81%</td>
<td>-3.0%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.86</td>
<td>99.81%</td>
<td>-3.0%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.87</td>
<td>98.56%</td>
<td>-3.0%</td>
<td>0.33</td>
</tr>
<tr>
<td>Run 7 180 × 180 × 36</td>
<td>4</td>
<td>0.87</td>
<td>100.00%</td>
<td>-3.0%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.87</td>
<td>99.92%</td>
<td>-3.0%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.87</td>
<td>98.90%</td>
<td>-3.1%</td>
<td>0.33</td>
</tr>
<tr>
<td>Run 8 180 × 180 × 100</td>
<td>4</td>
<td>0.88</td>
<td>100.00%</td>
<td>-3.2%</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.88</td>
<td>100.00%</td>
<td>-3.2%</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.88</td>
<td>99.96%</td>
<td>-3.2%</td>
<td>0.33</td>
</tr>
<tr>
<td>Run 9 240 × 240 × 16</td>
<td>4</td>
<td>0.86</td>
<td>98.78%</td>
<td>-1.9%</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.86</td>
<td>98.78%</td>
<td>-1.9%</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.87</td>
<td>97.11%</td>
<td>-1.9%</td>
<td>0.33</td>
</tr>
<tr>
<td>Run 10 240 × 240 × 100</td>
<td>4</td>
<td>0.89</td>
<td>100.00%</td>
<td>-3.5%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.89</td>
<td>100.00%</td>
<td>-3.5%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.89</td>
<td>100.00%</td>
<td>-3.5%</td>
<td>0.34</td>
</tr>
<tr>
<td>Run 11 270 × 270 × 100</td>
<td>4</td>
<td>0.89</td>
<td>100.00%</td>
<td>-3.5%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.89</td>
<td>100.00%</td>
<td>-3.5%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.89</td>
<td>100.00%</td>
<td>-3.5%</td>
<td>0.34</td>
</tr>
<tr>
<td>Run 12 360 × 360 × 16</td>
<td>4</td>
<td>0.88</td>
<td>99.81%</td>
<td>-1.9%</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.88</td>
<td>99.81%</td>
<td>-1.9%</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.88</td>
<td>98.78%</td>
<td>-1.9%</td>
<td>0.33</td>
</tr>
<tr>
<td>Run 13 360 × 360 × 36</td>
<td>4</td>
<td>0.89</td>
<td>100.00%</td>
<td>-3.2%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.89</td>
<td>100.00%</td>
<td>-3.2%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.89</td>
<td>100.00%</td>
<td>-3.2%</td>
<td>0.34</td>
</tr>
<tr>
<td>Geozone</td>
<td>505435</td>
<td>325</td>
<td>265</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>-------</td>
<td>-------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Search Radii</strong></td>
<td>Pass 1 90 m × 90 m × 50 m</td>
<td>180 m × 180 m × 50 m</td>
<td>180 m × 180 m × 50 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pass 2 180 m × 180 m 100 m</td>
<td>360 m × 360 m × 100 m</td>
<td>360 m × 360 m × 100 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Minimum Samples</strong></td>
<td>8</td>
<td>8</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Block Discretisation</strong></td>
<td>10 × 10 × 5</td>
<td>10 × 10 × 5</td>
<td>10 × 10 × 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Number of angular sectors</strong></td>
<td>8</td>
<td>8</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Optimum number of samples per sector</strong></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Select all samples in the target block</strong></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The search ellipses for two blocks within domain 505435 together with the drillholes and blocks are shown in Figure 5-1 and Figure 5-2. In these figures the drillholes are shown as grey cylinders and the blue dots are composites that would be used for estimation. Note that due to the other kriging parameters not all the composites in the ellipse will be selected for use.
The search ellipses for domain 505435 in cross section can be seen in Figure 5-3. This figure shows how the search ellipse for domain 505435 interacts with the topography and the domain itself. It can be seen that although the search ellipse z dimension is quite large this helps select composites from higher and lower elevations.
A cross validation plots for Fe within domain 505435 using search pass 1 is shown in Figure 5-4. The target variable at each composite data point is temporarily discarded and an estimate $Z^*$ of the value at this point is calculated by ordinary kriging, using its neighbourhood information (nearby composites). The results show that a problem as many points that were more than 60% Fe were estimated to be less than 60% Fe (see quadrant II of Figure 5-4). The line of best fit for the data is shown in black.
The scatterplots of true values against estimates for the other domains for search pass 1 are shown in Figure 5-5. The results for domain 325 indicate that the spread of data values was so large it was difficult to get reasonable estimates. The results for domain 265 were slightly better than those for domain 505435. The correlation coefficient was higher and there were fewer estimates where the true value was greater than 60% Fe and those that did occur are closer to the 60% line than was the case for domain 505435. The reason is a more pronounced clustering of composites greater than 60% Fe in this domain.

5.3 Ordinary Kriging Estimation

OK estimation was completed using the neighbourhoods and parameters defined in the previous section. The number of blocks estimated on the first pass and second pass for domain 505435 was 2441 (first pass) and 190 (second pass). For domain 325 the number of blocks estimated were 432 (first pass) and 53 (second pass) and for the final domain, 265, the number of blocks estimated were 676 (first pass) and 9 (second pass). The location of the blocks estimated on each pass for all domains is shown in Figure 5-6.
As part of the estimation the following values were calculated and stored for each block:

- The slope of regression (see Section 2.4);
- The number of composites used for estimation;
- The mean distance of composites used from the centroid of the block;

The slope of regression parameter is useful in assessing the quality of the estimates and histograms of this parameter for domain 505435 are shown in Figure 5-7 (first pass) and Figure 5-8 (second pass). The mean slope of regression was 0.76 and the blocks are plotted and coloured according to slope of regression value in Figure 5-6. The blocks with low values are located around the margins of the domain and further from drill composite data. The mean slopes of regression for domains 325 and 265 were 0.68 and 0.79 respectively.

The number of blocks estimated on the first pass and second pass for domain 505435 was 2441 (first pass) and 190 (second pass). For domain 325 the number of blocks estimated were 432 (first pass) and 53 (second pass) and for the final domain 265 the number of blocks estimated were 676 (first pass) and 9 (second pass).
Figure 5-7 Domain 505435 First Pass Slopes of Regression

Figure 5-8 Domain 505435 Second Pass Slopes of Regression

Figure 5-9 Domain 505435 Slopes of Regression (first and second passes)
Figure 5-10 OK Slope of Regression Results for all Domains

The mean distance of composites used to estimate blocks from the block centroid for domain 505435 is shown in Figure 5-11 (first pass), Figure 5-13 (second pass). The number of samples used to estimate blocks in domain 505435 for the first pass of OK was on average 16 and the mean distance of samples used to the centre of the blocks was 53 m. The numbers for the second pass of OK were 20 and 125 m.

Figure 5-11 Domain 505435 Histogram of Mean Distance of Samples to Blocks for First Pass

Figure 5-12 Domain 505435 Histogram of Number of Samples Used to Estimates Blocks for First Pass
5.4 Global Change of Support Estimation

Global change of support (GCoS) estimation provides a different estimate of resources (tonnes and grades) based on the assumption that the shape of the distribution is preserved when the support of the distribution changes. The GCoS estimate is not a local estimate at all but does give a grade tonnage curve for each domain.

The mining unit was set to 30 m × 30 m × 5 m because this size is the same as the block size of the OK, IK and Median IK estimates and so will make the results more comparable. Change of support estimates assume perfect selectivity i.e. all blocks can be mined, even isolated blocks. The composite samples of the three domains and variogram models for Fe, SiO₂ and Al₂O₃ composites may be used to generate a global change of support estimate for each domain.

The steps involved were:

1. Creation of a model of the point anamorphosis (composites);
2. Calculating the support correction using semivariogram model.

A point anamorphosis model of the histogram of the composite data for each of Fe, SiO₂ and Al₂O₃ in each domain was created using the first 40 Hermite polynomials. An example of the fit for domain 505435 Fe is shown in Figure 5-15, the composite data are shown in black and the model in blue.
The support correction factor was calculated and discussion on how this was done is included in Section 5.5. An affine correction was applied and the GCoS was computed on all the composites as well as composites filtered to lie within the pit after first creating a semivariogram model to represent these data.

5.5 Indicator Kriging Estimation

The indicators for each domain, threshold and attribute were estimated using ordinary kriging. The process used the same search neighbourhoods that were used in OK. The result of this was a discrete (informed at 11, 5, 5 thresholds respectively for the domains 505435, 325 and 265) conditional cumulative distribution function (ccdf) of points within the panel. The conditional probability that the panel value is greater than any of the thresholds may be inferred from the ccdf.

The data are then post processed for three reasons:

1. To interpolate within each class of thresholds and extrapolate beyond the smallest and largest threshold values in order to rebuild the local cumulative density function (cdf) for each grid node, in order to derive the tonnage and metal quantity for other cutoffs.
2. To correct for order relation problems with ccdf values that have resulted in a decreasing function at any threshold \( z \) i.e it is impossible that the probability of exceeding a grade at any threshold \( z_{k+1} \) is greater than the probability of exceeding at the same grade at \( z_k \). The order relation corrections were done according to the procedure outlined in Deutsch and Journel, 1998.

3. To make compensation to values for change of support from points to blocks.

Interpolation within classes was done using a linear model. The parameters for extrapolation for the upper and lower tails of the distributions were decided by assessing the shapes of the composite distributions, testing models on these and working out which parameters gave the best fit of this data.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Extrapolation Parameters</th>
<th>Fe</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>505435</td>
<td>Minimum Value Allowed</td>
<td>22</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Maximum Value Allowed</td>
<td>65</td>
<td>27</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>Lower Tail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Model</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Lower Power Weight</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Upper Tail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper Power Weight</td>
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<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Minimum Value Allowed</td>
<td>9</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Maximum Value Allowed</td>
<td>62</td>
<td>44</td>
<td>32</td>
</tr>
<tr>
<td>325</td>
<td>Lower Tail</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Power Model</td>
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<tr>
<td></td>
<td>Linear Model</td>
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<td>Lower Power Weight</td>
<td>3.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Upper Tail</td>
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</tr>
<tr>
<td></td>
<td>Power Model</td>
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<tr>
<td></td>
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<td>Minimum Value Allowed</td>
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<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Maximum Value Allowed</td>
<td>64</td>
<td>42</td>
<td>20</td>
</tr>
<tr>
<td>265</td>
<td>Lower Tail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Model</td>
<td></td>
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<tr>
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<td>Lower Power Weight</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Upper Tail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Model</td>
<td></td>
<td></td>
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<td></td>
<td>Power Model</td>
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</tr>
<tr>
<td></td>
<td>Upper Power Weight</td>
<td>0.5</td>
<td>0.3</td>
<td>0.25</td>
</tr>
</tbody>
</table>
In order to carry out the post processing a change of support or volume correction factor (F factor) must be decided on and this factor is the \( \frac{\text{SMU Variance}}{\text{Point Variance}} \). F factors were generated for 30 m \( \times \) 30 m \( \times \) 5 m blocks for GCoS processing and for 15 m \( \times \) 15 m \( \times \) 5 m for IK and Median IK post processing and are shown in Table 5-4. The discretisation of blocks (NX, NY and NZ) were tested to determine what discretisation gave the most stable result.

<table>
<thead>
<tr>
<th>Domain</th>
<th>SMU Size (m)</th>
<th>F Factor Fe</th>
<th>F Factor SiO(_2)</th>
<th>F Factor Al(_2)O(_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>505435</td>
<td>30 ( \times ) 30 ( \times ) 5</td>
<td>0.53</td>
<td>0.53</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>15 ( \times ) 15 ( \times ) 5</td>
<td>0.63</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>325</td>
<td>30 ( \times ) 30 ( \times ) 5</td>
<td>0.41</td>
<td>0.41</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>15 ( \times ) 15 ( \times ) 5</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>265</td>
<td>30 ( \times ) 30 ( \times ) 5</td>
<td>0.63</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>15 ( \times ) 15 ( \times ) 5</td>
<td>0.77</td>
<td>0.77</td>
<td>0.77</td>
</tr>
</tbody>
</table>

In summary in order to complete the estimation process search neighbourhoods were tested and selected and these were used for OK, IK and Median IK. A two pass search strategy was decided on and the searches chosen for the domain 505435 were 90 m \( \times \) 90 m \( \times \) 50 m and 180 m \( \times \) 180 m \( \times \) 100 m. For domains 325 and 265 the two searches were 180 m \( \times \) 180 m \( \times \) 50 m and 360 m \( \times \) 360 m \( \times \) 100 m.

Cross validation tests of each domain showed that estimating HG within domain 505435 would be problematic. Many HG composite points within this domain would be estimated as LG as the HG composites are spread though the domain. This is not so much of a problem in domain 265 as the HG samples are more clustered.
6 Results

This chapter contains the results from the OK, IK, Median IK and change of support estimates. The main purpose of this chapter is to assess the estimates against both the composite data used to derive them and production data. In the first four sections of this chapter the IK and Median IK results presented are restricted to the central estimates of grade for blocks, i.e the E-type estimates. The last section (6.4) makes use of the ccdf estimated for each block in the IK and Median IK results to create probability maps for Fe being greater than 60%. The results from the different methods are compared with each other and the drill hole data used to derive them in Section 6.1 and Section 6.2. The comparisons in Section 6.1 are qualitative and make use of plots and visual comparison whereas in Section 6.2 the comparisons are quantitative. The estimates are compared with production data in Section 6.3. Section 6.4 contains a suggested approach to make the best use of the IK and Median IK results. The main aspect of the results presented is the amount of HG estimated.

It was noted in Section 2.7 that the IK (and Median IK) results provide more than just a central estimate of grade, the additional information being an estimate of the ccdf of grades within a block. There are different ways of using this ccdf and two possible interpretations are:

1. Probabilities--: The probability that the grade is above a specified threshold; or

2. Proportions--: The proportion of the block above the specified threshold

In this thesis it is the first way that is used as the second assumes that any ore, even very small amounts, e.g. one tonne, will be recovered from the SMU. In practical terms the second method is only applicable to mining operations where the SMUs will be go through a sorting and treatment process in a plant or mill and ore extracted from the mass of rock. It does not matter so much in these operations that only part of the ore in the SMU is above the threshold, nor does it matter where it is within the SMU, as it will be recovered. In many iron ore operations there is very little processing of ore SMUs recovered from the mine so it is thus the average grade of the SMU that is important for reconciliation with production figures.

From a practical mining viewpoint, the GCoS estimates also have to be considered as not totally representative as to what may be mined as they assume perfect selectivity. This
means that if a block is greater than 60% it will be assumed to be mineable and in cases where the block is isolated this may not be practical.

6.1 Plots of Estimates Versus Composites

The estimates were viewed and compared against the composites. Plans showing the results for Fe were generated and are shown in Figure 6-1 (composites), Figure 6-2 (OK estimates), Figure 6-3 (IK E-type), and Figure 6-4 (Median IK E-type). Each figure shows data from all domains and in all the figures the colour of HG values is red.

From Figure 6-1 it can be seen that the most abundant composite Fe grades are between 55% and 60% Fe. HG composite values appear not to be very continuous from the data. When this figure is compared to the estimates the dominance of Fe grades between 55% and 60% Fe has been captured but the proportion of HG blocks is less. In most areas where there were few HG composites the estimates have values less than 60% Fe.

![Figure 6-1 Plan View of Composite Fe Grades](image-url)
Figure 6-2 Plan View of OK Estimate Fe Grades

Figure 6-3 Plan View of Fe IK E-type Estimates
Figure 6-4 Plan View of Fe Median IK E-type Estimates

The grades for the estimates and composite data were averaged on east section lines at 61 m intervals and then plotted. A tolerance of 30.5 m either side of each easting line was used so that no data were missed. The results for Domain 505435 Fe are shown in Figure 6-5. All the estimates are very close to each other and they are smoothed in comparison to the composites. Plots of all attributes in all domains can be seen in Appendix 5.

Figure 6-5 Swath Plot Domain 505435 Composites Vs Estimates by Easting for Fe
6.2 Statistics and Histograms

Statistics and histograms were generated for each domain in order to compare the result of the different estimates with each other and with the composites used to derive them. Full tables of all statistics for each domain are shown in Appendix 5. The means of the attributes for the composites and all estimation methods are shown in Table 6-1. For domains 505435 and 265 the means of the estimates are similar to the composites. For domain 325 the means of the estimates are slightly lower for Fe and higher for Al₂O₃ for all estimation methods. In the same domain the estimates were higher for SiO₂ for all estimation methods except OK.

### Table 6-1 Attribute Means by Domain and Source

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Source</th>
<th>505435</th>
<th>325</th>
<th>265</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Fe</strong></td>
<td>Composites</td>
<td>55.90</td>
<td>49.11</td>
<td>55.32</td>
</tr>
<tr>
<td></td>
<td>OK</td>
<td>56.04</td>
<td>48.72</td>
<td>55.08</td>
</tr>
<tr>
<td></td>
<td>IK E-type</td>
<td>55.93</td>
<td>47.29</td>
<td>54.71</td>
</tr>
<tr>
<td></td>
<td>Median IK E-type</td>
<td>55.92</td>
<td>47.28</td>
<td>54.77</td>
</tr>
<tr>
<td><strong>Mean SiO₂</strong></td>
<td>Composites</td>
<td>8.59</td>
<td>11.46</td>
<td>9.96</td>
</tr>
<tr>
<td></td>
<td>OK</td>
<td>8.27</td>
<td>10.96</td>
<td>9.79</td>
</tr>
<tr>
<td></td>
<td>IK E-type</td>
<td>8.23</td>
<td>11.90</td>
<td>9.70</td>
</tr>
<tr>
<td></td>
<td>Median IK E-type</td>
<td>8.24</td>
<td>11.84</td>
<td>9.65</td>
</tr>
<tr>
<td><strong>Mean Al₂O₃</strong></td>
<td>Composites</td>
<td>3.32</td>
<td>7.21</td>
<td>3.71</td>
</tr>
<tr>
<td></td>
<td>OK</td>
<td>3.27</td>
<td>7.26</td>
<td>3.89</td>
</tr>
<tr>
<td></td>
<td>IK E-type</td>
<td>3.34</td>
<td>8.50</td>
<td>3.69</td>
</tr>
<tr>
<td></td>
<td>Median IK E-type</td>
<td>3.35</td>
<td>8.49</td>
<td>3.68</td>
</tr>
</tbody>
</table>

The reason for the difference in mean grades for Domain 325 is that the samples are not evenly spread through the domain. This feature can be seen in Figure 4-5; in the northeast of this figure there are a significant number of blocks that are not represented in equivalent proportion by composites.

As noted in Section 4.3 the composite data show strong correlation between attributes. A graph comparing the correlations for composites and the estimates is shown in Figure 6-6 and it can be seen that the correlations between attributes have been preserved in the estimates. Tables of these statistics for the estimates are shown and compared to the composites in Appendix 5 for domains 325 and 265. Domain 265 has highly correlated Fe-Al₂O₃ (r = -0.89) results for the composites and there has been some loss of this correlation in the IK and Median IK E-type estimates (r = -0.71, r = -0.73 respectively). In the same domain there is some loss of the correlation between SiO₂ and Al₂O₃. This is possibly due to a small number of high Al₂O₃ data in the composites making the correlations higher than the other domains in the first place and these being smoothed in generating the E-type estimates.
Histogram plots of the composite data and the estimation methods for Fe in each domain are presented in Figure 6-7, Figure 6-8 and Figure 6-9, the purpose of these is to check how the shape of the composite histogram has been preserved in the estimates. It can be seen that from these figures the variance of the estimates is reduced in comparison to the composites for all attributes and for all domains. This is normal and ‘desired’ to some extent as the volume of the blocks is much greater than the composites. The GCoS histogram has a greater proportion of HG compared to the OK, IK E-type and Median IK E-type histograms, suggesting that the OK, IK E-type and Median IK E-type estimates are over-smoothed with respect to this cut-off. This aspect is explored more quantitatively in the next section.
Figure 6-7 Composites Vs Estimates Domain 505435 Fe
Figure 6-8 Composites Vs Estimates Domain 325 Fe
Figure 6-9 Composites Vs Blocks Domain 265
6.3 Reconciliation with Production Data

The production data, consisting of blocked out HG material were totalled and compared to the estimates for all domains within the June 2011 pit shell. In order to do this separate GCoS estimates were made for each domain within the pit shell using the same block size as the local estimates (30 m × 30 m × 5 m) and the results summed.

The totalled mining production data of HG are shown in the final row and column of Table 6-2. The total amount of HG blocked out for production was 6.393 Mt and the weighted average grade of this material was 61.68%. In comparison all the estimates are lower, for both tonnes and Fe grade. The closest estimate was made by GCoS with a total HG tonnage of 3.989 Mt at an average grade of 61.0% Fe. The best local estimator was OK which estimated a total HG tonnage of 1.958 Mt with an average Fe grade of 60.73%. The IK and Median IK E-type estimates are very similar to each other and significantly lower than the OK estimates (1.567 Mt and 1.593 Mt respectively) for tonnes and slightly lower than the OK estimates for grade.

<table>
<thead>
<tr>
<th>Source</th>
<th>Parameter</th>
<th>505435</th>
<th>325</th>
<th>265</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>OK</td>
<td>Mt</td>
<td>1.607</td>
<td>0</td>
<td>0.351</td>
<td>1.958</td>
</tr>
<tr>
<td></td>
<td>% Fe</td>
<td>60.74</td>
<td>60.66</td>
<td>60.36</td>
<td>60.73</td>
</tr>
<tr>
<td>GCoS</td>
<td>Mt</td>
<td>2.899</td>
<td>0.001</td>
<td>1.089</td>
<td>3.989</td>
</tr>
<tr>
<td></td>
<td>% Fe</td>
<td>61.01</td>
<td>61.19</td>
<td>61.03</td>
<td>61.02</td>
</tr>
<tr>
<td>IK E-type</td>
<td>Mt</td>
<td>1.364</td>
<td>0</td>
<td>0.203</td>
<td>1.567</td>
</tr>
<tr>
<td></td>
<td>% Fe</td>
<td>60.66</td>
<td>60.36</td>
<td>60.47</td>
<td>60.62</td>
</tr>
<tr>
<td>Median IK E-type</td>
<td>Mt</td>
<td>1.296</td>
<td>0</td>
<td>0.297</td>
<td>1.593</td>
</tr>
<tr>
<td></td>
<td>% Fe</td>
<td>60.64</td>
<td>60.47</td>
<td>60.61</td>
<td></td>
</tr>
<tr>
<td>Mining Data</td>
<td>Mt</td>
<td>5.282</td>
<td>0.083</td>
<td>1.028</td>
<td>6.393</td>
</tr>
<tr>
<td></td>
<td>% Fe</td>
<td>61.65</td>
<td>62.34</td>
<td>61.81</td>
<td>61.68</td>
</tr>
</tbody>
</table>

For domain 265 the GCoS estimate of tonnes is very accurate 1.089 Mt compared to the mining data 1.028 Mt although the grade estimated is a little lower.
Grade tonnage curves for domains 505435, 325 and 265 are shown in Figure 6-10 - Figure 6-12. Each chart shows a curve for each estimation method and a grey dashed line representing the curve for the production data. The IK E-Type estimate curve was not shown on these charts as it is so close to the Median IK E-Type curve it would be hidden.

The GCoS estimate curve is closest to the production data for all domains although it is still significantly lower. The OK and Median IK E-type curves are very similar and quite different from both the GCoS curve and the production data curve. The curves are furthest from the production data for domain 325 although very little of this domain is actually above the HG cut-off.

![Grade Tonnage Curves: Domain 505435 Inside June 2011 Pit](image)

**Figure 6-10 Grade Tonnage Curve for Domain 505435**
6.4 Making Full use of IK Information and a Risk Based Approach

The main information that IK and Median IK provide is an estimate of the ccdf for each block and this may be interpreted as the probability of each block estimate being greater than a threshold cut-off grade. Plots of this information were completed using the HG threshold and the results for IK and Median IK are shown in Figure 6-13 and Figure 6-14.
These plots compare favourably with the HG blocks marked out for production (Figure 6-15). There is a good match spatially at high probabilities and a reasonable match at low probabilities. Note that the pit does not extend to the same eastern and western limits as the estimates.
Blocks of different probabilities of being HG were assigned a tag of HG so that a Quantitative assessment of the percentage of HG correctly classified could be made against the HG blocked out during production. The tonnes of HG and percentage of correctly classified at different probabilities is shown in Table 6-3. It can be seen that at higher probabilities lower tonnages of HG material were estimated and higher percentages of this were correctly classified. The amount of material with a 20% or more chance of being HG was 10.4 Mt and 43% of this was correctly classified as HG. It can be seen that the closest match of production tonnes (6.4 Mt) is close to the blocks with a probability of 0.3 of being HG.

<table>
<thead>
<tr>
<th>Probability of being HG</th>
<th>Tonnes (Kt) above Threshold</th>
<th>Percentage Correctly Classified</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>22,924</td>
<td>27</td>
</tr>
<tr>
<td>0.1</td>
<td>14,891</td>
<td>36</td>
</tr>
<tr>
<td>0.2</td>
<td>10,394</td>
<td>43</td>
</tr>
<tr>
<td>0.3</td>
<td>6,745</td>
<td>49</td>
</tr>
<tr>
<td>0.4</td>
<td>4,528</td>
<td>54</td>
</tr>
<tr>
<td>0.5</td>
<td>2,763</td>
<td>55</td>
</tr>
<tr>
<td>0.6</td>
<td>1,468</td>
<td>59</td>
</tr>
</tbody>
</table>
Plots of blocks with probabilities of being HG of 0.5, 0.4, 0.3 and 0.2 superimposed on the HG blocks marked out for production are shown in Figure 6-16 through to Figure 6-19 inclusively. These plots highlight the spatial match at each probability. Blocks with a probability of 0.5 of being HG lie within or very close to HG blocks blocked out during mining. At a lower probability of 0.2 of being HG there is still a good spatial match with most estimated blocks still very close to the production HG blocks.

These maps of locations of probable HG are much better than the map of location of HG blocks provided by OK, IK E-type or Median IK E-type. These central estimates provide a very conservative view the amount of HG with a large amount of sub HG material estimated.

It should also be noted that the IK and Median IK methods produce very similar results. This is a significant point because the amount of work required to complete Median IK is far less than IK; as only one semivariogram model is required for each attribute within a domain.

The probability plots can be generated for other attributes. An interesting threshold for Al₂O₃ is 3 % as material above this threshold is very likely to contain shale and clay and be attractive to process though a concentrating plant. A plot of the results showing probability of exceeding this threshold is shown in Figure 6-20.
Figure 6-16 IK Probability of being HG of 0.5 and HG Grade Blocks (Red)

Figure 6-17 IK Probability of being HG of 0.4 and HG Grade Blocks (Red)
Figure 6-18 IK Probability of being HG of 0.3 and HG Grade Blocks (Red)

Figure 6-19 IK Probability of being HG of 0.2 and HG Grade Blocks (Red)
Figure 6-20 IK Probability of blocks being greater than 3% Al₂O₃
7 Summary and Concluding Remarks

The aim of this thesis was to investigate how to use information gained from Ordinary Kriging, Global Change of Support (GCoS), Indicator Kriging (IK) and Median IK estimation in defining iron ore resources in hardcap domains. Of particular interest was the ability of each method to categorise selective mining units as High Grade (HG) Ore ($\geq 60\%$ Fe) as this is the most valuable ore.

The objectives of this thesis were to:

- Assess the information provided by the techniques of OK, GCoS and IK (including Median IK) against each other and production data.
- Examine the extra information provided by IK and Median IK and determine if this is useful and may be exploited in estimating HG.
- Devise a methodology to get the best result in estimating HG.

In order to achieve this aim and the objectives a deposit was chosen that was substantially mined out and had production data that could be used to test the results of the estimates. Three hardcap domains were geologically modelled from drillhole data spaced at 60 m, blast hole data spaced at 7 m and some ground and in-pit mapping. Each of the three hardcap domains had a high variability of Fe, SiO$_2$ and Al$_2$O$_3$ assay data related to the different lithologies and weathering present in these domains. Variations in the lithology within the domains can occur over short distances however some continuity was observed in the experimental semivariograms and this continuity was modelled. A multi-pass search strategy was devised to take into account the end use of the model, relevance of nearby samples and quantitative neighbourhood kriging results. Cross-validation tests of neighbourhoods selected for use indicated that estimation of HG in domain 505435 would be problematical. For each domain local estimates were produced for each of the three attributes using OK, IK, and Median IK. A GCoS estimate of each domain was also completed.

The estimates were compared to the composites used to derive them and production data. Means of the estimates compared reasonably to the estimates but excessive smoothing of the OK, IK E-type and Median IK E-type results was observed in histograms and plan plots of grade. Comparisons of the grade/tonnage curves showed a high degree of smoothing of these central estimates of grade compared to the GCoS estimate. The smoothing had a
large impact on the tonnes of HG estimated to be present. The OK estimate of tonnes of HG present was 2.0 Mt compared to the GCoS estimate of 4.0 Mt.

The production data showed conclusively that the OK estimate was very inaccurate and over-smoothed as the amount of HG actually recovered during mining from the hydrated domains was 6.4 Mt. It can be concluded that the OK estimation run at this deposit gave a poor estimate of the tonnes of HG present and that the best check for over-smoothing was a combination of plan plots of grade, histograms and the use of GCoS estimates.

With regard to the IK and Median IK results firstly it must be recognised that they provide more information than OK. This is because the OK estimates of the indicators produce, after post processing, a ccdf of each block rather than just a central estimate of grade. From the ccdf the average grade (E-Type estimates) may be obtained and also the results may be interpreted as probabilities that the block is above a threshold. The other possible use for the ccdf as proportions of tonnes and grades of blocks above thresholds is not valid for this thesis as we would be assuming that each SMU would be post processed in a plant to metallurgically extract every last tonne of iron ore from each SMU. For the deposit considered in this thesis and for most iron ore deposits SMUs are assigned their final classification (ore, low grade or waste) prior to mining using blast hole results and there is no post-processing of SMU to extract ore.

The E-type estimates available from IK or Median IK were also inaccurate (1.2 Mt and 1.4 Mt respectively) and it may be concluded that these results have also been smoothed with regard to the cut-off. This smoothing has not occurred due to choice of tail extrapolation parameters as the HG cut-off value was at or below the last threshold for every domain. We can conclude that IK and Median IK E-Type estimates do not give any better result than OK. We can also conclude that the ability of either method to classify in a strict sense blocks as HG is poor.

All the central estimate of grades (OK, IK and Median IK E-type) were inaccurate and over smoothed. Given good quality samples and assays as well as sound estimation parameters (which are present) the accuracy of these methods fundamentally comes down to the amount of data available to estimate from. We can conclude that there is insufficient data to get accurate estimates using these techniques.
The ccdf estimated for each block by IK or Median IK may be interpreted as a probability of each block being HG, the very existence of a non-zero probability of a block exceeding the HG threshold, can be used as a classification aid. Plots of blocks with probabilities of being HG ranging from 0.5- 0.2 were plotted against the ‘true’ HG grade blocks and there is a good spatial match. Blocks that have a 0.5 probability of being HG do not fully cover the area of ‘true’ HG whereas blocks with a probability of 0.2 of being HG extend slightly outside this area. Median IK was just as useful as IK in achieving this and this is an important practical consideration as Median IK is a lot less work than OK.

Using Median IK probability results to identify areas that have some probability of being HG gives a much improved result for data considered in this thesis. One must recall the two maps of HG the OK version being very few blocks of HG and a ‘sea’ of sub 60% Fe material and the Median IK version providing ‘clouds’ of HG blocks which better represent reality. This technique makes better use of the data available and provides more information to the geologist or mine planner than a single estimate of block grade for an attribute. It also allows for a higher or lower risk of finding HG.

The methodology may be extended to other deposits and other domains. In practice a lot of focus on using iron ore models is on the absolute determination of economic category, in the case of the deposit in this thesis people using the model for planning will want to know is the material HG or not. OK and IK central estimates of grade may not be suitable for providing this information and GCoS estimates can be used for checking, and comparing postplots of composite and estimate grades as well as histograms of the same data. In the past OK or central grade estimates have been used to estimate domains and if an issue with smoothing has been identified then this has simply been deemed a risk without any further aid or action provided. A suggested approach to this sort of problem that combines OK, GCoS and Median IK is outlined below and would potentially be a big improvement.

It is proposed that if OK has been used in estimating the hardcap domain and if the GCoS estimate indicates that there is a risk of over-smoothing with regard to the HG cut-off then Median IK should be used to identify areas which have a chance of being HG and then deciding on the best way to take advantage of this information. Some possibilities would be to:

- target these areas for closer spaced drilling in order to generate an improved OK estimate;
• use the area defined above to sub-domain the hardcap and re-estimate using OK;
• target these areas for mining first as they have a good chance of being HG.

The first two suggestions, once completed, require the subsequent estimation of the domain(s) by OK.

The level of risk that is regarded as acceptable may be decided depending on the intended outcomes. For example if a high level of risk is thought to be appropriate then the areas defined above may be by probability of being high grade of only 10%, if a lower risk is thought to be appropriate then the areas defined may be by a probability of being HG of 80%. It may in some situations be appropriate to commence work in lower risk areas and leave work in the higher risk areas to later.
References

Appendix 1. **OK Semivariogram Maps and Parameters for Experimental Semivariograms. Q-Q plots for samples RC Vs OH.**

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
</tr>
</thead>
</table>

**Appendix Figure 1-1 Domain 325 Composite Semivariogram Map**

**Appendix Figure 1-2 Domain 265 Composite Semivariogram Map**
Experimental semivariogram were generated in Isatis. The 5m composite file was imported and selections (sel) defined by domains. Interval Selections were defined for the Hardcap in Joffre (265), Whaleback Shale (325) and Dales Gorge plus FWZ (505+435).

Appendix Figure 1-3 Experimental Variogram Parameters Regular and Normal Directions

Appendix Figure 1-4 Definition of Reference Plane
Appendix Figure 1-5 QQ Plots: Fe Open Hole Vs Reverse Circulation Samples for Domains 265, 325, 505435
Appendix 2. **Indicator Semivariogram Maps**

**Domain 505435 Indicator Semivariogram Maps**

<table>
<thead>
<tr>
<th>Fe 46.04°</th>
<th>Fe 50.00°</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Indicator Semivariogram Maps" /></td>
<td><img src="image2.png" alt="Indicator Semivariogram Maps" /></td>
</tr>
</tbody>
</table>

Legend: 
- Red: High Indicator Semivariogram
- Blue: Low Indicator Semivariogram
- Black: No Indicator Semivariogram
Domain 325 Indicator Semivariogram Maps

Variogram Map - FE_325_IK(47.030000)

Variogram Map - FE_325_IK(50.000000)

Variogram Map - FE_325_IK(55.000000)

Variogram Map - FE_325_IK(58.230000)

Variogram Map - FE_325_IK(60.000000)
Domain 265 Indicator Semivariogram Maps

Variogram Map - FE_325_IK(47.030000)

Variogram Map - FE_325_IK(50.000000)

Variogram Map - FE_325_IK(55.000000)

Variogram Map - FE_325_IK(58.230000)

Variogram Map - FE_325_IK(60.000000)
Appendix 3. **Indicator Semivariogram Models**
Comps/Lines(Sel: 505+435)
- Variable #1 : AL2O3_505435_IK(0.960000)
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.02
S2 - Spherical - Range = 15.00m, Sill = 0.017
  Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 24.00m, Sill = 0.011
  Directional Scales = ( 420.00m, 420.00m, 24.00m
Comps/Lines(Sel: 505+435)
- Variable #1 : AL2O3_505435_IK{1.220000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.037
S2 - Spherical - Range = 15.00m, Sill = 0.032
  Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 24.00m, Sill = 0.021
  Directional Scales = ( 360.00m, 360.00m, 24.00m

Variogram Model - Global Window

Isatis

Comps/Lines(Sel: 505+435)
- Variable #1 : AL2O3_505435_IK{1.680000}
Experimental Variogram : in 1 direction(s)
D1 : N90
   Angular tolerance = 90.00
   Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.068
S2 - Spherical - Range = 15.00m, Sill = 0.057
   Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 24.00m, Sill = 0.037
   Directional Scales = ( 220.00m, 220.00m, 24.00m

Distance (m)
Comps/Lines (Sel: 505+435)
- Variable #1: AL2O3_505435_IK{2.000000}
Experimental Variogram: in 1 direction(s)
D1: N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.088
S2 - Spherical - Range = 15.00m, Sill = 0.075
  Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.048
  Directional Scales = (200.00m, 200.00m, 24.00m)
Variogram Model - Global Window

- Variable #1: AL2O3_505435_IK{2.500000}

Experimental Variogram: in 1 direction(s)

D2: N20

Angular tolerance = 15.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)

S1 - Nugget effect, Sill = 0.103
S2 - Spherical - Range = 22.00m, Sill = 0.086
   Directional Scales = ( 70.00m, 70.00m, 22.00m
S3 - Spherical - Range = 22.00m, Sill = 0.057
   Directional Scales = ( 200.00m, 100.00m, 22.00m

Comps/Lines(Sel: 505+435)

Isatis
Isatis
Comps/Lines(Sel: 505+435)
- Variable #1 : AL2O3_505435_IK(2.760000)
Experimental Variogram : in 1 direction(s)
D2  : N20
    Angular tolerance = 15.00
    Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1  - Nugget effect, Sill = 0.132
S2  - Spherical - Range = 26.00m, Sill = 0.063
    Directional Scales = (140.00m, 100.00m, 26.00m)
S3  - Spherical - Range = 26.00m, Sill = 0.055
    Directional Scales = (260.00m, 100.00m, 26.00m)
Variogram Model - Global Window

Comps/Lines (Sel: 505+435)
- Variable #1: AL2O3_505435_IK{3.000000}
Experimental Variogram: in 1 direction(s)
D2 : N20
  Angular tolerance = 15.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.13
S2 - Spherical - Range = 24.00m, Sill = 0.062
Directional Scales = (160.00m, 100.00m, 24.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.055
Directional Scales = (240.00m, 100.00m, 24.00m)
Variogram Model - Global Window

Isatis
Comps/Lines (Sel: 505+435)
- Variable #1 : AL2O3_505435_IK{3.710000}
Experimental Variogram : in 1 direction(s)
D2 : N20
  Angular tolerance = 15.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.092
S2 - Spherical - Range = 16.00m, Sill = 0.053
  Directional Scales = ( 70.00m, 70.00m, 16.00m
S3 - Spherical - Range = 24.00m, Sill = 0.064
  Directional Scales = ( 360.00m, 120.00m, 24.00m
Variogram Model - Global Window

Comps/Lines (Sel: 505+435)
- Variable #1: AL2O3_505435_IK\{4.500000\}
Experimental Variogram: in 1 direction(s)
D2: N20
   Angular tolerance = 15.00
   Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.05
S2 - Spherical - Range = 16.00m, Sill = 0.04
   Directional Scales = (70.00m, 60.00m, 16.00m)
S3 - Spherical - Range = 16.00m, Sill = 0.07
   Directional Scales = (280.00m, 180.00m, 16.00m)
Isatis

Comps/Lines (Sel: 505+435)
- Variable #1: AL2O3_505435_IK{6.030000}

Experimental Variogram: in 1 direction(s)
D2 : N20
    Angular tolerance = 15.00
    Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)

S1 - Nugget effect, Sill = 0.016
S2 - Spherical - Range = 8.00m, Sill = 0.029
    Directional Scales = (90.00m, 60.00m, 8.00m)
S3 - Spherical - Range = 10.00m, Sill = 0.045
    Directional Scales = (300.00m, 120.00m, 10.00m)
Isatis

Comps/Lines (Sel: 505+435)
- Variable #1: AL2O3_505435_IK{7.640000}

Experimental Variogram: in 1 direction(s)
D2: N20
   Angular tolerance = 15.00
   Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%

Model: 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.008
S2 - Spherical - Range = 8.00m, Sill = 0.016
   Directional Scales = (140.00m, 120.00m, 8.00m)
S3 - Spherical - Range = 8.00m, Sill = 0.024
   Directional Scales = (140.00m, 120.00m, 8.00m)
Isatis

Comps/Lines(Sel: 505+435)
- Variable #1 : FE_505435_IK{46.040000}
Experimental Variogram : in 1 direction(s)
D2 : N20
  Angular tolerance = 15.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.008
S2 - Spherical - Range = 8.00m, Sill = 0.016
  Directional Scales = ( 180.00m, 100.00m, 8.00m
S3 - Spherical - Range = 8.00m, Sill = 0.024
  Directional Scales = ( 180.00m, 100.00m, 8.00m
Isatis
Comps/Lines (Sel: 505+435)
- Variable #1 : FE_505435_IK{50.000000}
Experimental Variogram : in 1 direction(s)
D2 : N20
  Angular tolerance = 15.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.018
S2 - Spherical - Range = 8.00m, Sill = 0.033
  Directional Scales = (200.00m, 100.00m, 8.00m)
S3 - Spherical - Range = 12.00m, Sill = 0.051
  Directional Scales = (240.00m, 100.00m, 12.00m)
Isatis

Comps/Lines (Sel: 505+435)
- Variable #1 : FE_505435_IK{52.310000}
Experimental Variogram : in 1 direction(s)
D2 - N20
  Angular tolerance = 15.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.05
S2 - Spherical - Range = 16.00m, Sill = 0.04
  Directional Scales = ( 70.00m, 60.00m, 16.00m
S3 - Spherical - Range = 16.00m, Sill = 0.07
  Directional Scales = ( 360.00m, 180.00m, 16.00m
Variogram Model - Global Window

Experimental Variogram: in 1 direction(s)
D2 : N20
    Angular tolerance = 15.00
    Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.1
S2 - Spherical - Range = 16.00m, Sill = 0.057
    Directional Scales = ( 70.00m, 70.00m, 16.00m
S3 - Spherical - Range = 24.00m, Sill = 0.07
    Directional Scales = ( 360.00m, 120.00m, 24.00m

Comps/Lines (Sel: 505+435)
- Variable #1: FE_505435_IK{55.000000}
Isatis
Comps/Lines (Sel: 505+435)
- Variable #1: FE_505435_IK{55.650000}
Experimental Variogram: in 1 direction(s)
D2 : N20
   Angular tolerance = 15.00
   Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.126
S2 - Spherical - Range = 20.00m, Sill = 0.06
   Directional Scales = (140.00m, 70.00m, 20.00m)
S3 - Spherical - Range = 20.00m, Sill = 0.053
   Directional Scales = (320.00m, 100.00m, 20.00m)
Isatis
Comps/Lines (Sel: 505+435)
- Variable #1 : FE_505435_IK{56.800000}
Experimental Variogram : in 1 direction(s)
D2 : N20
  Angular tolerance = 15.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.132
S2 - Spherical - Range = 24.00m, Sill = 0.063
  Directional Scales = (140.00m, 100.00m, 24.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.055
  Directional Scales = (280.00m, 100.00m, 24.00m)
Variogram Model - Global Window

- Variable #1: FE_505435_IK{57.850000}

Experimental Variogram: in 1 direction(s)
D2: N20

Angular tolerance = 15.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%

Model: 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)

S1 - Nugget effect, Sill = 0.1
S2 - Spherical - Range = 22.00m, Sill = 0.084
  Directional Scales = (70.00m, 70.00m, 22.00m)
S3 - Spherical - Range = 22.00m, Sill = 0.056
  Directional Scales = (240.00m, 100.00m, 22.00m)
Isatis
Comps/Lines (Sel: 505+435)
- Variable #1 : FE_505435_IK{59.030000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.087
S2 - Spherical - Range = 15.00m, Sill = 0.074
  Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 24.00m, Sill = 0.048
  Directional Scales = ( 160.00m, 160.00m, 24.00m
Variogram Model - Global Window

Isatis
Comps/Lines(Sel: 505+435)
- Variable #1 : FE_505435IK{60.000000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.071
S2 - Spherical - Range = 15.00m, Sill = 0.06
  Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 24.00m, Sill = 0.039
  Directional Scales = ( 160.00m, 160.00m, 24.00m
Comps/Lines (Sel: 505+435)
- Variable #1: FE_505435_IK{61.510000}
Experimental Variogram: in 1 direction(s)
D1: N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.038
S2 - Spherical - Range = 15.00m, Sill = 0.032
  Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.021
  Directional Scales = (130.00m, 130.00m, 24.00m)
Isatis
Comps/Lines (Sel: 505+435)
- Variable #1: FE_505435_IK{62.470000}
Experimental Variogram: in 1 direction(s)
D1: N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.021
S2 - Spherical - Range = 15.00m, Sill = 0.017
  Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.012
  Directional Scales = (100.00m, 100.00m, 24.00m)
Comps/Lines (Sel: 505+435)
- Variable #1: SIO2_505435_IK{2.730000}
Experimental Variogram: in 1 direction(s)
D1: N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.02
S2 - Spherical - Range = 15.00m, Sill = 0.017
  Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 20.00m, Sill = 0.011
  Directional Scales = ( 500.00m, 500.00m, 20.00m

Variogram Model - Global Window
Experimental Variogram: in 1 direction(s)

D1: N90
Angular tolerance = 90.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.037
S2 - Spherical - Range = 15.00m, Sill = 0.031
    Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.021
    Directional Scales = (500.00m, 500.00m, 24.00m)
Variogram Model - Global Window

Comps/Lines (Sel: 505+435)
- Variable #1: SIO2_505435ÎK{4.830000}

Experimental Variogram: in 1 direction(s)
D1: N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%

Model: 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.067
S2 - Spherical - Range = 15.00m, Sill = 0.057
  Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.037
  Directional Scales = (300.00m, 300.00m, 24.00m)
Isatis
Comps/Lines(Sel: 505+435)
- Variable #1 : SIO2_505435_IK{5.670000}
Experimental Variogram : in 1 direction(s)
D1 : N90
    Angular tolerance = 90.00
    Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.088
S2 - Spherical - Range = 15.00m, Sill = 0.075
    Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 24.00m, Sill = 0.048
    Directional Scales = ( 200.00m, 200.00m, 24.00m
Variogram Model - Global Window

Isatis

Comps/Lines(Sel: 505+435)
- Variable #1 : SIO2_505435_IK{6.400000}
Experimental Variogram : in 1 direction(s)
D2  : N20
  Angular tolerance = 15.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1  - Nugget effect, Sill = 0.1
S2  - Spherical - Range = 18.00m, Sill = 0.084
    Directional Scales = ( 70.00m, 70.00m, 18.00m
S3  - Spherical - Range = 22.00m, Sill = 0.056
    Directional Scales = ( 280.00m, 100.00m, 22.00m
Variogram Model - Global Window

Experimental Variogram: in 1 direction(s)
D2 : N20
  Angular tolerance = 15.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.132
S2 - Spherical - Range = 24.00m, Sill = 0.063
  Directional Scales = (140.00m, 100.00m, 24.00m
S3 - Spherical - Range = 24.00m, Sill = 0.055
  Directional Scales = (240.00m, 100.00m, 24.00m

Isatis
Comps/Lines (Sel: 505+435)
- Variable #1: SIO2_505435_IK{7.280000}

Distance (m)
Isatis

Comps/Lines(Sel: 505+435)
- Variable #1 : SIO2_505435_IK{8.250000}
Experimental Variogram : in 1 direction(s)
D2 : N20
  Angular tolerance = 15.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1  - Nugget effect, Sill = 0.126
S2  - Spherical - Range = 24.00m, Sill = 0.06
Directional Scales = ( 70.00m, 70.00m, 24.00m
S3  - Spherical - Range = 24.00m, Sill = 0.053
Directional Scales = ( 300.00m, 100.00m, 24.00m

Variogram Model - Global Window

Variogram : SIO2_505435_IK{8.250000}

Angular tolerance = 15.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1  - Nugget effect, Sill = 0.126
S2  - Spherical - Range = 24.00m, Sill = 0.06
Directional Scales = ( 70.00m, 70.00m, 24.00m
S3  - Spherical - Range = 24.00m, Sill = 0.053
Directional Scales = ( 300.00m, 100.00m, 24.00m
Variogram Model - Global Window

Isatis

Comps/Lines (Sel: 505+435)
- Variable #1: SIO2_505435_IK{9.710000}

Experimental Variogram: in 1 direction(s)
D2 : N20
  - Angular tolerance = 15.00
  - Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%

Model: 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.092
S2 - Spherical - Range = 16.00m, Sill = 0.053
  Directional Scales = ( 70.00m, 70.00m, 16.00m
S3 - Spherical - Range = 24.00m, Sill = 0.064
  Directional Scales = ( 250.00m, 120.00m, 24.00m
Isatis

Comps/Lines(Sel: 505+435)
- Variable #1 : SIO2_505435_IK[11.530000]
Experimental Variogram : in 1 direction(s)
D2 : N20
   Angular tolerance = 15.00
   Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.05
S2 - Spherical - Range = 16.00m, Sill = 0.04
   Directional Scales = ( 70.00m, 60.00m, 16.00m
S3 - Spherical - Range = 16.00m, Sill = 0.07
   Directional Scales = ( 280.00m, 180.00m, 16.00m
Variogram Model - Global Window

- Variable #1 : SIO2_505435_IK{15.190000}
Experimental Variogram : in 1 direction(s)
D2 : N20
  Angular tolerance = 15.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.016
S2 - Spherical - Range = 8.00m, Sill = 0.029
  Directional Scales = ( 200.00m, 100.00m, 8.00m
S3 - Spherical - Range = 14.00m, Sill = 0.045
  Directional Scales = ( 300.00m, 100.00m, 14.00m
Isatis
Comps/Lines(Sel: 505+435)
- Variable #1 : SIO2_505435_IK[18.820000]
Experimental Variogram : in 1 direction(s)
D2 : N20
   Angular tolerance = 15.00
   Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N290.00 (Geologist)
S1 - Nugget effect, Sill = 0.008
S2 - Spherical - Range = 8.00m, Sill = 0.016
   Directional Scales = ( 200.00m, 100.00m, 8.00m
S3 - Spherical - Range = 12.00m, Sill = 0.024
   Directional Scales = ( 320.00m, 120.00m, 12.00m
Isatis
Comps/Lines(Sel: 325)
- Variable #1 : AL2O3_325_IK{2.500000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.023
S2 - Spherical - Range = 15.00m, Sill = 0.001
  Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.001
  Directional Scales = (120.00m, 120.00m, 24.00m)
Comps/Lines (Sel: 325)
- Variable #1: AL2O3_325_IK{3.000000}
Experimental Variogram: in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth= N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.046
S2 - Spherical - Range = 15.00m, Sill = 0.019
  Directional Scales = ( 90.00m, 90.00m, 15.00m
S3 - Spherical - Range = 24.00m, Sill = 0.019
  Directional Scales = ( 200.00m, 200.00m, 24.00m

Isatis

Comps/Lines (Sel: 325)
- Variable #1: AL2O3_325_IK{4.200000}

Experimental Variogram: in 1 direction(s)
D1: N90
Angular tolerance = 90.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%

Model: 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.085
S2 - Spherical - Range = 15.00m, Sill = 0.036
  Directional Scales = (90.00m, 90.00m, 15.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.036
  Directional Scales = (160.00m, 160.00m, 24.00m)
Experimental Variogram : in 1 direction(s)

D1 : N90

Angular tolerance = 90.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%

Model : 3 basic structure(s)

Global rotation = Azimuth=N77.00 (Geologist)

S1 - Nugget effect, Sill = 0.137
S2 - Spherical - Range = 9.00m, Sill = 0.057
  Directional Scales = (70.00m, 70.00m, 9.00m)
S3 - Spherical - Range = 9.00m, Sill = 0.057
  Directional Scales = (70.00m, 70.00m, 9.00m)
Experimental Variogram : in 1 direction(s)
D1 : N90
    Angular tolerance = 90.00
    Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.115
S2 - Spherical - Range = 12.00m, Sill = 0.047
    Directional Scales = ( 70.00m, 70.00m, 12.00m
S3 - Spherical - Range = 16.00m, Sill = 0.047
    Directional Scales = ( 90.00m, 90.00m, 16.00m

Isatis
Comps/Lines(Sel: 325)
- Variable #1 : AL2O3_325_IK{7.430000}
Variogram Model - Global Window

**Variogram : FE_325_IK{47.030000}**

Isatis
Comps/Lines(Sel: 325)
- Variable #1 : FE_325_IK{47.030000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.117
S2 - Spherical - Range = 12.00m, Sill = 0.048
  Directional Scales = (70.00m, 70.00m, 12.00m)
S3 - Spherical - Range = 16.00m, Sill = 0.048
  Directional Scales = (90.00m, 90.00m, 16.00m)
Isatis
Comps/Lines(Sel: 325)
- Variable #1 : FE_325_IK{50.000000}
Experimental Variogram : in 1 direction(s)
D1 : N90
   Angular tolerance = 90.00
   Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.135
S2 - Spherical - Range = 9.00m, Sill = 0.056
   Directional Scales = (70.00m, 70.00m, 9.00m)
S3 - Spherical - Range = 9.00m, Sill = 0.056
   Directional Scales = (70.00m, 70.00m, 9.00m)
Comps/Lines(Sel: 325)
- Variable #1 : FE_325_IK{55.000000}
Experimental Variogram : in 1 direction(s)
  D1 : N90
    Angular tolerance =  90.00
    Lag =  60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill =  0.099
S2 - Spherical - Range = 15.00m, Sill =  0.042
    Directional Scales = (  90.00m,  90.00m,  15.00m
S3 - Spherical - Range = 24.00m, Sill =  0.042
    Directional Scales = ( 160.00m, 160.00m, 24.00m
Variogram Model - Global Window

Comps/Lines (Sel: 325)
- Variable #1: FE_325_IK{58.230000}

Experimental Variogram: in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.05
S2 - Spherical - Range = 15.00m, Sill = 0.021
  Directional Scales = (90.00m, 90.00m, 15.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.021
  Directional Scales = (200.00m, 200.00m, 24.00m)
Variogram Model - Global Window

Isatis
Comps/Lines(Sel: 325)
- Variable #1 : FE_325_IK{60.000000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.015
S2 - Spherical - Range = 15.00m, Sill = 0.0008
  Directional Scales = ( 60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.0008
  Directional Scales = ( 120.00m, 120.00m, 24.00m)
Variogram Model - Global Window

Isatis

Comps/Lines(Sel: 325)
- Variable #1 : SIO2_325_IK{2.510000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance =  90.00
  Lag =  60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.044
S2 - Spherical - Range = 15.00m, Sill = 0.0024
  Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 24.00m, Sill = 0.0024
  Directional Scales = ( 120.00m, 120.00m, 24.00m
Comps/Lines(Sel: 325)
- Variable #1 : SIO2_325_IK{2.900000}
Experimental Variogram : in 1 direction(s)
D1 : N90
Angular tolerance =  90.00
Lag =  60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill =  0.046
S2 - Spherical - Range = 15.00m, Sill =  0.019
    Directional Scales = (  90.00m,  90.00m,  15.00m
S3 - Spherical - Range = 24.00m, Sill =  0.019
    Directional Scales = (  200.00m,  200.00m,  24.00m
Variogram Model - Global Window

Comps/Lines (Sel: 325)
- Variable #1: SIO2_325_IK{5.750000}
Experimental Variogram: in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.085
S2 - Spherical - Range = 15.00m, Sill = 0.036
  Directional Scales = (90.00m, 90.00m, 15.00m)
S3 - Spherical - Range = 24.00m, Sill = 0.036
  Directional Scales = (160.00m, 160.00m, 24.00m)
Variogram Model - Global Window

Isatis
Comps/Lines(Sel: 325)
- Variable #1 : SIO2_325_IK{9.410000}
Experimental Variogram : in 1 direction(s)
D1 : N90
   Angular tolerance = 90.00
   Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.137
S2 - Spherical - Range = 9.00m, Sill = 0.057
   Directional Scales = ( 70.00m, 70.00m, 9.00m
S3 - Spherical - Range = 9.00m, Sill = 0.057
   Directional Scales = ( 70.00m, 70.00m, 9.00m
Variogram Model - Global Window

Comps/Lines(Sel: 325)
- Variable #1 : SIO2_325_IK{13.480000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N77.00 (Geologist)
S1 - Nugget effect, Sill = 0.115
S2 - Spherical - Range = 12.00m, Sill = 0.047
  Directional Scales = (70.00m, 70.00m, 12.00m)
S3 - Spherical - Range = 16.00m, Sill = 0.047
  Directional Scales = (90.00m, 90.00m, 16.00m)
Comps/Lines(Sel: 265)
- Variable #1 : AL2O3_265_IK{1.770000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance =  90.00
  Lag =  60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N0.00 (Geologist)
S1 - Nugget effect, Sill = 0.053
S2 - Spherical - Range = 15.00m, Sill = 0.035
  Directional Scales = (40.00m, 40.00m, 15.00m)
S3 - Spherical - Range = 20.00m, Sill = 0.074
  Directional Scales = (70.00m, 70.00m, 20.00m)
Variogram Model - Global Window

Isatis
Comps/Lines(Sel: 265)
- Variable #1 : AL2O3_265_IK{2.500000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=NO.00 (Geologist)
S1 - Nugget effect, Sill = 0.078
S2 - Spherical - Range = 15.00m, Sill = 0.05
  Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 20.00m, Sill = 0.109
  Directional Scales = ( 120.00m, 120.00m, 20.00m
Isatis

Comps/Lines(Sel: 265)
- Variable #1 : AL203_265LIK{3.000000}
Experimental Variogram : in 1 direction(s)
D1 : N90
   Angular tolerance = 90.00
   Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N0.00 (Geologist)
S1 - Nugget effect, Sill = 0.082
S2 - Spherical - Range = 15.00m, Sill = 0.053
   Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 20.00m, Sill = 0.114
   Directional Scales = (120.00m, 120.00m, 20.00m)
Experimental Variogram : in 1 direction(s)

D1 : N90

Angular tolerance = 90.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%

Model : 3 basic structure(s)

Global rotation = Azimuth=N0.00 (Geologist)

S1 - Nugget effect, Sill = 0.068
S2 - Spherical - Range = 15.00m, Sill = 0.085
  Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 15.00m, Sill = 0.055
  Directional Scales = ( 200.00m, 200.00m, 15.00m
Variogram Model - Global Window

Comps/Lines (Sel: 265)
- Variable #1: AL2O3_265_IK{6.520000}
Experimental Variogram: in 1 direction(s)
D1: N90

Angular tolerance = 90.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%

Model: 3 basic structure(s)
Global rotation = Azimuth=NO.00 (Geologist)
S1 - Nugget effect, Sill = 0.03008
S2 - Spherical - Range = 15.00m, Sill = 0.01946
  Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 20.00m, Sill = 0.04246
  Directional Scales = (70.00m, 70.00m, 20.00m)
Experimental Variogram : in 1 direction(s)

D1 : N90

Angular tolerance = 90.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%

Model : 3 basic structure(s)

- Nugget effect, Sill = 0.034
- Spherical - Range = 15.00m, Sill = 0.022
  Directional Scales = (60.00m, 60.00m, 15.00m)
- Spherical - Range = 20.00m, Sill = 0.048
  Directional Scales = (70.00m, 70.00m, 20.00m)
Variogram Model - Global Window

Comps/Lines(Sel: 265)
- Variable #1: FE_265_IK{55.000000}

Experimental Variogram: in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N0.00 (Geologist)
S1 - Nugget effect, Sill = 0.068
S2 - Spherical - Range = 15.00m, Sill = 0.085
  Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 15.00m, Sill = 0.055
  Directional Scales = (200.00m, 200.00m, 15.00m)
Variogram Model - Global Window

Comps/Lines (Sel: 265)
- Variable #1: FE_265_IK{57.060000}
Experimental Variogram: in 1 direction(s)
D1: N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N0.00 (Geologist)
S1 - Nugget effect, Sill = 0.082
S2 - Spherical - Range = 15.00m, Sill = 0.053
  Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 20.00m, Sill = 0.115
  Directional Scales = (120.00m, 120.00m, 20.00m)
Variogram Model - Global Window

Isatis

Comps/Lines (Sel: 265)
- Variable #1 : FE_265_IK{58.160000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N0.00 (Geologist)
S1 - Nugget effect, Sill = 0.079
S2 - Spherical - Range = 15.00m, Sill = 0.051
  Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 20.00m, Sill = 0.11
  Directional Scales = (120.00m, 120.00m, 20.00m)
Variogram Model - Global Window

Experimental Variogram: in 1 direction(s)
D1: N90
Angular tolerance = 90.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N0.00 (Geologist)
S1 - Nugget effect, Sill = 0.046
S2 - Spherical - Range = 15.00m, Sill = 0.03
   Directional Scales = (40.00m, 40.00m, 15.00m)
S3 - Spherical - Range = 20.00m, Sill = 0.064
   Directional Scales = (70.00m, 70.00m, 20.00m)
Variogram Model - Global Window

**Comps/Lines (Sel: 265)**
- Variable #1: SIO2_265_IK{5.470000}

**Experimental Variogram:** in 1 direction(s)

**D1:** N90
- Angular tolerance = 90.00
- Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%

**Model:** 3 basic structure(s)

**Global rotation = Azimuth=N0.00 (Geologist)**

**S1:** - Nugget effect, Sill = 0.053

**S2:** - Spherical - Range = 15.00m, Sill = 0.035
    - Directional Scales = (40.00m, 40.00m, 15.00m)

**S3:** - Spherical - Range = 20.00m, Sill = 0.074
    - Directional Scales = (70.00m, 70.00m, 20.00m)
Variogram Model - Global Window

Experimental Variogram: in 1 direction(s)
- Direction: N90

- Lag: 60.00 m, Count: 10 lags, Tolerance: 50.00%
- Angular tolerance: 90.00
- Global rotation: Azimuth = N0.00 (Geologist)

Model: 3 basic structure(s)
- S1: Nugget effect, Sill = 0.079
- S2: Spherical, Range = 15.00 m, Sill = 0.051
  Directional Scales: (60.00 m, 60.00 m, 15.00 m)
- S3: Spherical, Range = 20.00 m, Sill = 0.11
  Directional Scales: (120.00 m, 120.00 m, 20.00 m)

Comps/Lines (Sel: 265)
- Variable #1: SIO2_265_IK{7.920000}

Isatis
Comps/Lines (Sel: 265)
- Variable #1 : SIO2_265_IK{8.630000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
Global rotation = Azimuth=N0.00 (Geologist)
S1 - Nugget effect, Sill = 0.082
S2 - Spherical - Range = 15.00m, Sill = 0.053
  Directional Scales = ( 60.00m, 60.00m, 15.00m
S3 - Spherical - Range = 20.00m, Sill = 0.115
  Directional Scales = ( 120.00m, 120.00m, 20.00m
Isatis

Comps/Lines(Sel: 265)
- Variable #1 : SIO2_265_IK{10.610000}
Experimental Variogram : in 1 direction(s)
D1 : N90
  Angular tolerance = 90.00
  Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model : 3 basic structure(s)
  Global rotation = Azimuth=N0.00 (Geologist)
  S1 - Nugget effect, Sill = 0.06865
  S2 - Spherical - Range = 15.00m, Sill = 0.08582
    Directional Scales = ( 60.00m, 60.00m, 15.00m)
  S3 - Spherical - Range = 15.00m, Sill = 0.05553
    Directional Scales = ( 200.00m, 200.00m, 15.00m)
Variogram Model - Global Window

Experimental Variogram: in 1 direction(s)
D1: N90
Angular tolerance = 90.00
Lag = 60.00m, Count = 10 lags, Tolerance = 50.00%
Model: 3 basic structure(s)
Global rotation = Azimuth=N0.00 (Geologist)
S1 - Nugget effect, Sill = 0.03
S2 - Spherical - Range = 15.00m, Sill = 0.019
  Directional Scales = (60.00m, 60.00m, 15.00m)
S3 - Spherical - Range = 20.00m, Sill = 0.042
  Directional Scales = (70.00m, 70.00m, 20.00m)
Appendix 4. Search Parameter Testing

### Appendix Table 4-1 Results of Neighbourhood Testing Domain 325 Fe

<table>
<thead>
<tr>
<th>Run Number (Search radius in metres X × Y × Z)</th>
<th>Minimum Number of Samples</th>
<th>Slope Z/Z* Mean</th>
<th>% Blocks Filled</th>
<th>Negative weights Mean</th>
<th>Weight of mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1 180 × 180 × 50</td>
<td>2</td>
<td>0.67</td>
<td>99.79%</td>
<td>-2.06%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.68</td>
<td>98.35%</td>
<td>-2.08%</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.71</td>
<td>89.07%</td>
<td>-2.26%</td>
<td>0.43</td>
</tr>
<tr>
<td>Run 2 360 × 360 × 36</td>
<td>2</td>
<td>0.70</td>
<td>100.00%</td>
<td>-2.65%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.71</td>
<td>98.76%</td>
<td>-2.66%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.72</td>
<td>94.85%</td>
<td>-2.77%</td>
<td>0.45</td>
</tr>
<tr>
<td>Run 3 360 × 360 × 100</td>
<td>2</td>
<td>0.70</td>
<td>100.00%</td>
<td>-2.13%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.70</td>
<td>100.00%</td>
<td>-2.13%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.70</td>
<td>100.00%</td>
<td>-2.13%</td>
<td>0.46</td>
</tr>
<tr>
<td>Run 4 420 × 420 × 100</td>
<td>2</td>
<td>0.72</td>
<td>100.00%</td>
<td>-2.58%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.72</td>
<td>100.00%</td>
<td>-2.58%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.72</td>
<td>100.00%</td>
<td>-2.58%</td>
<td>0.46</td>
</tr>
<tr>
<td>Run 5 480 × 480 × 100</td>
<td>2</td>
<td>0.72</td>
<td>100.00%</td>
<td>-2.59%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.72</td>
<td>100.00%</td>
<td>-2.59%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.72</td>
<td>100.00%</td>
<td>-2.59%</td>
<td>0.46</td>
</tr>
<tr>
<td>Run 6 560 × 560 × 56</td>
<td>2</td>
<td>0.72</td>
<td>100.00%</td>
<td>-2.65%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.72</td>
<td>100.00%</td>
<td>-2.65%</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.72</td>
<td>100.00%</td>
<td>-2.65%</td>
<td>0.46</td>
</tr>
</tbody>
</table>

### Appendix Table 4-2 Domain 325 Slope of Regression SiO₂ and Al₂O₃

<table>
<thead>
<tr>
<th>Run Number (Search radius in metres X × Y × Z)</th>
<th>Minimum Number of Samples</th>
<th>Slope Z/Z* Mean SiO₂</th>
<th>Slope Z/Z* Mean Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1 180 × 180 × 50</td>
<td>2</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.68</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.71</td>
<td>0.72</td>
</tr>
<tr>
<td>Run 2 360 × 360 × 36</td>
<td>2</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.71</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>Run 3 360 × 360 × 100</td>
<td>2</td>
<td>0.71</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.71</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.71</td>
<td>0.71</td>
</tr>
<tr>
<td>Run 4 420 × 420 × 100</td>
<td>2</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>Run 5 480 × 480 × 100</td>
<td>2</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>Run 6 560 × 560 × 56</td>
<td>2</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>Run Number</td>
<td>Minimum Number of Samples</td>
<td>Slope Z/Z* Mean</td>
<td>% Blocks Filled</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------------</td>
<td>-----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Run 1</td>
<td>2</td>
<td>0.80</td>
<td>99.71%</td>
</tr>
<tr>
<td>180 × 180 × 50</td>
<td>4</td>
<td>0.80</td>
<td>99.56%</td>
</tr>
<tr>
<td>Run 2</td>
<td>8</td>
<td>0.80</td>
<td>98.69%</td>
</tr>
<tr>
<td>270 × 270 × 36</td>
<td>4</td>
<td>0.82</td>
<td>99.71%</td>
</tr>
<tr>
<td>Run 3</td>
<td>8</td>
<td>0.82</td>
<td>98.69%</td>
</tr>
<tr>
<td>360 × 360 × 36</td>
<td>4</td>
<td>0.82</td>
<td>99.56%</td>
</tr>
<tr>
<td>Run 4</td>
<td>8</td>
<td>0.82</td>
<td>98.83%</td>
</tr>
<tr>
<td>360 × 360 × 100</td>
<td>8</td>
<td>0.80</td>
<td>100.00%</td>
</tr>
<tr>
<td>Run 5</td>
<td>8</td>
<td>0.80</td>
<td>100.00%</td>
</tr>
<tr>
<td>480 × 480 × 48</td>
<td>4</td>
<td>0.82</td>
<td>100.00%</td>
</tr>
<tr>
<td>Run 6</td>
<td>8</td>
<td>0.82</td>
<td>99.56%</td>
</tr>
<tr>
<td>480 × 480 × 64</td>
<td>4</td>
<td>0.82</td>
<td>100.00%</td>
</tr>
<tr>
<td>Run 7</td>
<td>8</td>
<td>0.82</td>
<td>100.00%</td>
</tr>
<tr>
<td>540 × 540 × 60</td>
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<td>0.82</td>
<td>100.00%</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.82</td>
<td>100.00%</td>
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### Appendix Table 4-4 Results of Neighbourhood Testing Domain 265 Fe

<table>
<thead>
<tr>
<th>Run Number (Search radius in metres X Y Z)</th>
<th>Minimum Number of Samples</th>
<th>Slope Z/Z* Mean SiO2</th>
<th>Slope Z/Z* Mean Al2O3</th>
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<tbody>
<tr>
<td>Run 1 180 × 180 × 50</td>
<td>2</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Run 2 270 × 270 × 36</td>
<td>2</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>Run 3 360 × 360 × 36</td>
<td>2</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>Run 4 360 × 360 × 100</td>
<td>2</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Run 5 480 × 480 × 48</td>
<td>2</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>4</td>
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<td>0.82</td>
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<tr>
<td></td>
<td>8</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>Run 6 480 × 480 × 64</td>
<td>2</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.82</td>
<td>0.82</td>
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<tr>
<td></td>
<td>8</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>Run 7 540 × 540 × 60</td>
<td>2</td>
<td>0.82</td>
<td>0.82</td>
</tr>
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<td></td>
<td>4</td>
<td>0.82</td>
<td>0.82</td>
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<tr>
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<td>8</td>
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<td>0.82</td>
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Appendix Figure 4-1 Domain 505435 Fe Cross Validation (90 m search)
Appendix Figure 4-2 Domain 505435 SiO₂ Cross Validation (90 m search)
Appendix Figure 4-3 Domain 505435 Al₂O₃ Cross Validation (90 m search)

- rho = 0.566

- rho = 0.055

- Nb Samples: 688
  - Minimum:  -5.91862
  - Maximum:  3.20898
  - Mean:     -0.0174012
  - Std. Dev.: 0.951731
Appendix Figure 4-4 Domain 325 Fe Cross Validation (180 m search)
Appendix Figure 4-5 Domain 325 SiO$_2$ Cross Validation (180 m search)

**Graph 1:**
- X-axis: X (m)
- Y-axis: Y (m)
- Title: rho = 0.337

**Graph 2:**
- X-axis: Z (m)
- Y-axis: Z* (Estimates)
- Title: rho = 0.163

**Graph 3:**
- X-axis: Nb Samples: 104
- Minimum: -4.11534
- Maximum: 1.9885
- Mean: 0.014326
- Std. Dev.: 1.03123

**Graph 4:**
- X-axis: Z* (Estimates)
- Y-axis: Frequencies
- Title: Nb Samples: 104
- Minimum: -4.11534
- Maximum: 1.9885
- Mean: 0.014326
- Std. Dev.: 1.03123
Appendix Figure 4-6 Domain 325 Al₂O₃ Cross Validation (180 m search)
Appendix Figure 4-7 Domain 265 Fe Cross Validation (180 m search)
Appendix Figure 4-8 Domain 265 SiO2 Cross Validation (180 m search)
Appendix Figure 4-9 Domain 265 Al2O3 Cross Validation (180 m search)
Appendix 5. **Summary Statistics, Swath Plots, and Validation Histograms**

This Appendix contains summary statistics, histograms, and correlations comparing the various estimates with the composites used to derive them. Firstly the summary statistics of the three estimates shall be listed in separate tables for each domain. Appendix Table 5-1 shows the summary statistics for Domain 505435, Appendix Table 5-2, and Appendix Table 5-3 show them for Domains 325 and 265 respectively.

For all attributes in Domains 505435 and 265 the means for composites, OK, IK E-type, and Median IK E-type estimates are similar. In Domain 325 however the IK mean is significantly lower than the OK or composite mean for Fe and significantly higher than the OK or composite mean for SiO₂ and Al₂O₃. In this domain the skewness of the Al₂O₃ data has changed sign and the skewness of the Fe data has very nearly changed sign.
## Appendix Table 5-1 Domain 505435 Statistics for Unweighted Composites and Blocks

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Data</th>
<th>CompsNW</th>
<th>OK</th>
<th>IK E-type</th>
<th>Median IK E-type</th>
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<tbody>
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<td><strong>Fe</strong></td>
<td>Count</td>
<td>727</td>
<td>2631</td>
<td>2631</td>
<td>2631</td>
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<tr>
<td></td>
<td>Minimum</td>
<td>22.286</td>
<td>37.455</td>
<td>42.946</td>
<td>44.412</td>
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<tr>
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<td>Maximum</td>
<td>64.54</td>
<td>62.29</td>
<td>62.09</td>
<td>61.807</td>
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<tr>
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<td>Mean</td>
<td>55.901</td>
<td>56.04</td>
<td>55.925</td>
<td>55.919</td>
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<tr>
<td></td>
<td>Std. Dev.</td>
<td>5.404</td>
<td>3.027</td>
<td>3.075</td>
<td>2.891</td>
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<tr>
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<td>Variance</td>
<td>29.2</td>
<td>9.16</td>
<td>9.453</td>
<td>8.358</td>
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<td>Variat.Coeff.</td>
<td>0.097</td>
<td>0.054</td>
<td>0.055</td>
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<td>7.209</td>
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<td>Minimum</td>
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<td>2.937</td>
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<td>8.233</td>
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<td>Minimum</td>
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<td>5.597</td>
<td>5.498</td>
<td>4.363</td>
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## Appendix Table 5-2 Domain 325 Statistics for Unweighted Composites and Blocks

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<th>IK E-type</th>
<th>Median IK E-type</th>
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<tbody>
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<td><strong>Fe</strong></td>
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<td>9.564</td>
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### Appendix Table 5-3 Domain 265 Statistics for Unweighted Composites and Blocks

<table>
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<th>CompsNW</th>
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<th>IK E-type</th>
<th>Median IK E-type</th>
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<td>685</td>
<td>685</td>
</tr>
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<td>55.077</td>
<td>54.71</td>
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<tr>
<td>SiO₂</td>
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Appendix Figure 5-1 Domain 505435 Fe Histograms
Appendix Figure 5-2 Domain 505435 SiO₂ Histograms
Appendix Figure 5-3 Domain 505435 Al$_2$O$_3$ Histograms
Appendix Figure 5-4 Domain 325 Fe Histograms
Appendix Figure 5-5 Domain 325 SiO$_2$ Histograms
Appendix Figure 5-6 Domain 325 Al₂O₃ Histograms
Appendix Figure 5-7 Domain 265 Fe Histograms
Appendix Figure 5-8 Domain 265 SiO₂ Histograms
Appendix Figure 5-9 Domain 265 Al₂O₃ Histograms
Swath Plots

Appendix Figure 5-10 Swath Plots Domain 505435
Appendix Figure 5-11 Swath Plots Domain 325
Appendix Figure 5-12 Swath Plots Domain 265
The correlation tables (Appendix Table 5-4, Appendix Table 5-5, Appendix Table 5-6) show that the OK estimates match the correlations that existed for the composites in all domains better than the IK and Median IK E-type.

Domain 265 has highly correlated Fe-Al₂O₃ (r = -0.89) results for the composites and there has been some loss of this correlation in the IK and Median IK E-type estimates (r = -0.71, r = -0.73 respectively). In the same domain there is some loss of the correlation between SiO₂ and Al₂O₃. This is possibly due to a small number of high Al₂O₃ data in the composites making the correlations higher than the other domains in the first place and these being smoothed in generating the E-type estimates.

### Appendix Table 5-4 Correlation Statistics Composites/OK Estimates/IK Estimates Domain 505435

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### Appendix Table 5-5 Correlation Statistics Composites/OK Estimates/IK Estimates Domain 325

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Estimates of Other Attributes (SiO$_2$ and Al$_2$O$_3$)

Appendix Figure 5-13 Composites SiO$_2$ All Domains

Appendix Figure 5-14 OK Estimates SiO$_2$ All Domains
Appendix Figure 5-15 IK E-type Estimates SiO$_2$ All Domains

Appendix Figure 5-16 Median IK E-type Estimates SiO$_2$ All Domains