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Geostatistical optimisation of sampling and estimation in a nickel laterite deposit

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Geostatistical Optimisation of Sampling and Estimation

in a Nickel Laterite Deposit

A Thesis Submitted to the
Faculty of Communications, Health and Science
Edith Cowan University
Perth, Western Australia

by Mark P. Murphy

In Fulfillment of the Requirements for the Degree
of
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Supervisors: Associate Professor Lyn Bloom

Dr Ute Mueller
USE OF THESIS

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Abstract

Nickel and cobalt are key additives to metal alloys in modern industry. The largest worldwide nickel-cobalt resources occur in nickel laterite deposits that have formed during the chemical weathering of ultramafic rocks at the Earth's surface. At the Murrin Murrin mine in Western Australia, the nickel laterite deposits occur as laterally extensive, undulating blankets of mineralisation with strong vertical anisotropy, near normal nickel distributions, and positively skewed cobalt distributions.

The mineral resources in nickel laterite deposits in Murrin Murrin are usually estimated from drilling and sampling on relatively wide-spaced drill patterns that are supported by local clusters of close-spaced sampling. The combination of deposit geometry and sampling configuration presents several estimation challenges for geostatistical resource estimation methods.

In this thesis, close-spaced grade control drill sampling data from Murrin Murrin is used to quantify the estimation effectiveness of the wider spaced actual exploration pattern used to define the original resource, and an alternative cost saving stratified sampling pattern. Additionally, an unfolding of the laterite blanket by vertical data translation prior to nickel and cobalt grade estimation is tested for each exploration pattern. The unfolding essentially removes undulations in the laterite blanket prior to grade estimation by vertical translation of the sample data relative to a surface of high grade nickel-cobalt connectivity. Unfolding is ex-
pected to improve estimation accuracy in terms of grade and volume, as well as improve the quality of variography analyses. The stratified pattern is expected to give similar estimation accuracy to the actual exploration pattern.

The effectiveness of ordinary kriging and full indicator kriging estimation algorithms from GSLIB software are compared for the combinations of in situ and unfolded cases of the actual sampling pattern used to define the deposit and an alternative stratified sampling pattern. For each combination, the estimates are made at the data locations of the close-spaced grade control ‘reality’. The accuracy of each estimate is quantified by comparing the error, degree of bias and pseudo grade-volume relationships of the estimate to the ‘reality’ data. Additionally, the quality of exploration pattern variography is assessed against the grade continuity of the grade control information. Importantly, the main focus of these comparisons is on the correct estimation of local high grade nickel and cobalt resources that are preferentially processed in the early years mining.

The results of comparisons between estimation methods and sample configuration combinations investigated show that the combination of unfolding and indicator kriging gives the best correspondence (in terms of grade and volume) of the various estimates to the grade control reality. The results of comparisons between the actual and the alternative stratified exploration pattern show that the cost saving alternative pattern produces estimates similar to the actual exploration estimates.
Declaration

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

(i.) incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

(ii.) contain any material previously published or written by another person except where due reference is made in the text; or

(iii.) contain any defamatory material

Signature

Date 11 August 2003
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1 INTRODUCTION

The research presented in this thesis deals with sampling and geostatistical nickel-cobalt grade estimation in a nickel laterite deposit in Western Australia. In order to fully appreciate the significance of this research, a geological and geostatistical framework for resource estimation of nickel laterite deposits is required. Several interrelated areas of geology and mathematics are relevant to the outcomes of this study including:

- the economic uses and sources of the metals nickel and cobalt,
- the geological processes which form nickel laterite deposits, and
- the geostatistical and geometric methods used to estimate the deposit metal grades.

The first two of the areas listed above is discussed in the following sections of Chapter 1 and the background to geostatistical estimation methods are detailed in Chapter 2. Chapter 3 discusses the important issues of sampling optimisation and resource geometry as a precursor to stating the principal hypotheses and investigations to be carried out to test the hypotheses. Chapter 4 describes the dataset used in the testing, and Chapter 5 the details grade continuity analyses on the research dataset that were used as inputs to the grade estimates described in Chapter 6. Chapter 7 details the conclusions drawn from the hypothesis testing.
1.1 Nickel and cobalt

Nickel and cobalt are important base metals in modern industry and are used mainly in high temperature and/or corrosion resistant metal alloys. Over 60% of the annual production of nickel is used in stainless steel products ["The Nickel Page", 2000] and 25% of primary cobalt is consumed in the production of superalloys for the aerospace and gas turbine industries. One major producer has estimated that world demand for these metals over the coming years will be one million tonnes of nickel metal per annum ["Falconbridge Newsletter", 1999], and over 30,000 tonnes of cobalt metal per annum. Based on current production levels of these metals, discovery and development of new mineral deposits will be required to meet these levels of demand.

In 2001, worldwide nickel reserves of deposits grading >1% Ni were estimated to contain 160 million tonnes of nickel metal [Nickel Statistics, 2002]. Approximately 60% of these reserves occur in near surface laterite deposits and the remainder are found in deeper underground nickel sulphide deposits. Despite the smaller proportion of world resources of nickel in sulphide deposits, approximately 35% of the total production is won from these deeper ores due to the higher average deposit grade [Brand et.al., 1998]. However, based on current projections of nickel demand, and the decreasing exploration success in finding sulphide deposits, the nickel laterite deposits have become a primary focus of many mining or exploration companies.
1.2 *Nickel laterite deposits*

Nickel laterite deposits form by the chemical weathering at the Earth’s surface of ultramafic rocks rich in the minerals olivine and/or serpentine. During the formation of the regolith (weathering profile) over these rocks, nickel and cobalt are concentrated ten-fold from low concentrations in source rocks, in the order of 0.3% Ni and 0.01% Co, to economically attractive levels in the order of 1.0 to 2.0% Ni and 0.1 to 0.5% Co. The degree of metal enrichment is controlled by deposit type and mode of formation. The enrichment process is a complex interplay of geochemical and geological processes, involving the formation of new minerals from the parent rocks and the loss of a substantial part of the original rock chemistry and mass to percolating ground waters [Golightly, 1981].

Approximately 85% of nickel laterite resources have formed from geologically young (<65 million years) ocean floor rocks that have been thrust to the surface in current tropical environments. The other 15% have formed over ancient (>500 million years) ultramafic rocks in arid continental interiors. However, initial formation of some of these deposits was at a time when continental drift had also located the rocks in the tropics (Figure 1.1).
The olivine-rich hosts and rapid enrichment processes of the tropical laterites result in the highest average nickel grades. However, many of the lower grade, dry climate deposits occur in regions that have significant economic advantages including lower topographic relief, better infrastructure, and more stable political environments.

Globally, nickel laterite deposits can be classified into three classes comprising silicate, clay or iron oxide dominated mineralogy [Brand et.al., 1998]. The key stratigraphic features of the regolith for these deposit styles are shown in Figure 1.2 with the coloured bars to left of each profile indicating the parts of the profile that become enriched to economically attractive metal concentrations of nickel and cobalt.
For each of the deposit styles, a generalised four-layer stratigraphy can be recognised, starting at depth with a basement ultramafic overlain by saprolite (decomposed parent rock with preserved mineral textures). Above the saprolite layer, complete rock weathering produces iron oxide and/or clay layers with a hard ferruginous cap at the surface. Dry climate and transitional deposit styles have deeper and thicker zones of economic mineralisation whereas tropical types are shallow with higher average nickel grades.

1.3 Western Australian nickel laterite deposits

Over the past decade, several Western Australian nickel-cobalt deposits commenced production from dry and transitional climate types. The development of these deposits has resulted from advances in materials science technology, the proximity of, and improvements in, infrastructure within Western Australia, and
reductions in acid production costs ["Australian Nickel Renaissance", 1999]. The economically viable deposits range in resource size from below 100 million tonnes to several deposits such as Murrin Murrin, with resources exceeding 200 million tonnes. The average economic metal grades of these deposits is in the order of 1.0% Ni and 0.05% Co. Selective mining and/or metallurgical upgrading methods have resulted in plant feed grades exceeding 1.25% Ni and 0.10% Co [Robinson, 1998].

The general geometry of Western Australian nickel laterite deposits can be described as elongate, flat lying, undulating near-surface blankets of mineralisation covering basement ultramafic rocks over strike extents of a few kilometres, to tens of kilometres [Fazakerley and Monti, 1998; Hellsten et.al, 1998]. Lateral widths range from hundreds to thousands of metres and the mineralised regolith averages 10 to 50 meters in thickness (Figure 1.3).
The blanket style geometry of these deposits combined with the strong vertical zonation of the minerals and associated metals, present particular problems in the correct estimation of the volume and metals grades of the deposits. The estimation issues, which are discussed in detail in Chapter 3, relate both to the sampling pattern used at the exploration stage and the methods used to estimate the resources from the available sampling information. However, prior to discussion of the issues, a background of the geostatistical estimation approaches is required.
2 GEOSTATISTICAL BACKGROUND

Geostatistics refers to a theoretical framework, together with a suite of mathematical methods, for quantitatively describing natural variables distributed in space. The theory and techniques of geostatistics are a synthesis of standard mathematical methods such as concepts of stationary random functions, methods of analysis of variance and least squares regression evaluation [Matheron, 1963; Journel, 1986]. The practical application of geostatistics to ore deposit evaluation is a standard practice in the Western Australian mining industry.

The following outline of geostatistical concepts is largely summarised from Goovaerts [1997]. The scope of the discussion is limited to those areas that are applicable to the current research. Other key authors are cited when necessary.

The roots of geostatistics go back to the late 1930's involving time-series analysis research. South African gold mines developed these ideas further from a mining standpoint for grade estimation [Krige, 1994]. However, the start of the current mathematical formulations and more advanced methods of geostatistics can mainly be attributed to Georges Matheron who used the term geostatistics extensively in his description of the 'Theory of Regionalized Variables' [Matheron, 1963].

In geostatistical mineral resource estimation, quantitative spatial models are inferred from the available sample data and are then applied to estimate key attributes at unsampled locations. Specifically, a sample-set of \( n \) measurements of an attribute \( z \) in the study region \( A \subseteq \mathbb{R}^3 \) is denoted by the set \( S = \{ z(u_\alpha), u_\alpha \in A, \alpha = 1, \ldots, n \} \) and can be regarded as a subset of the population
\{z(\mathbf{u}), \mathbf{u} \in \mathcal{A}\} \text{ of all measurements of } z \text{ that could be made over } \mathcal{A}. \text{ When the measurements are not exhaustive, which is always the case in resource estimation, it is necessary to model the spatial distribution of } z \text{ over } \mathcal{A}. \text{ Matheron [1963] described a spatially distributed attribute forming a very large but finite population within a given region as a regionalised variable.}

Matheron explained in an early text on mining geostatistics, that in the case of mineral deposits "ore grades are of mixed character, being both structured and random" and "... a scientific (or at least, simply realistic) estimation must take into account both features" [Journel and Huijbregts, 1978]. Matheron applied both probabilistic and deterministic concepts to model these dual aspects. The methods he developed provided a consistent approach to predicting the values at unsampled locations. The first assumption of geostatistical theory is therefore to view a set of measurements at unsampled locations as values of a set of random variables, as described below.

2.1 Random variables

A random variable, Z, is a real value function defined by a sample set that describes the possible values of an attribute z within a particular sample space. The behaviour of a random variable is not random in the sense that there is no predictable outcome, but more that the values of the random variable can generally be characterised by a probability function that assigns probabilities to particular values [Deutsch and Journel, 1998].

In mineral resource estimation, continuous random variables, which have an ordered, unbroken range of possible values are often used to model metal grades.
The following descriptions therefore focus on continuous random variables and associated indicator transforms.

Following convention, a continuous random variable is denoted with the upper case letter $Z$ while its values are denoted in corresponding lower case $z$. Typically, the random variable is location dependent so the notation is modified to $Z(u)$ where $u$ represents the spatial coordinates. For a location dependent, continuous random variable $Z(u)$, the univariate cumulative frequency distribution fully characterises the variable and for each $z \in \mathbb{R}$, gives the probability that the value at $u$ is no greater than a $z$ threshold of interest (Equation 1).

$$F(u;z) = \text{Prob}\{Z(u) \leq z\} \quad -\infty < z < \infty \quad (1)$$

The cumulative probability of $Z(u)$ lies within $[0,1]$ (Equation 2) and the cumulative frequency distribution is a non-decreasing function of the $z$ threshold (Equation 3) for all $z$

$$F(u;z) \in [0,1] \quad (2)$$

and

$$F(u;z) \leq F(u;z') \text{ whenever } z \leq z'. \quad (3)$$

The derivative with respect to $z$ of the cumulative distribution function $F(u;z)$, when it exists, is the probability density function $f(u;z)$.

An indicator random variable is binary. When applied to the class of continuous random variables, an indicator random variable is defined by the probability that
Z(u) is no greater than a particular threshold of z. Values not exceeding the
threshold are assigned a one. Otherwise, the assignment is zero (Equation 4).

\[
I(u;z) = \begin{cases} 
1 & \text{if } Z(u) \leq z \\
0 & \text{otherwise} 
\end{cases}
\]  

(4)
The probability of not exceeding the z-threshold is equivalent to the expected
value (or mean outcome) of the indicator random variable \( I(u;z) \) (Equation 5).

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

(5)
The random variable approach to resource estimation of metal grades is to
conceptualise all sampled and unsampled values at locations within the study area
as values of a set of random variables \( Z(u) \). For a continuous random variable,
this assumption requires the definition of a conditional cumulative distribution
function at the location \( u \) (Equation 6).

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

(6)
Equation 1 defines a model of the uncertainty prior to using nearby information,
whilst Equation 6 models the posterior uncertainty once the conditioning informa-
tion has been incorporated into the model. The goal in geostatistical modelling is
to update the prior models into posterior models; this updating is achieved through
further assumptions introduced under the concept of a random function as dis-

cussed below.

### 2.2 Random functions

A random function is defined as a set of (usually) dependent random variables,
\( Z(u) \) that have outcomes at locations \( u \) within a study region \( A \); \{Z(u), u \in A \}. Similar to the way the cumulative frequency distribution characterises a random
variable $Z(u)$, the multivariate cumulative frequency distribution characterises the random function $Z(u)$. Specifically, the realisation of a random function at $N$ locations $u_k$ ($k = 1, \ldots, N$) is a vector of random variables $\{Z(u_1), \ldots, Z(u_N)\}$ and this set is characterised by the multivariate cumulative frequency distribution (Equation 7).

$$F(u_1, \ldots, u_N; z_1, \ldots, z_N) = \text{Prob}\{Z(u_1) \leq z_1, \ldots, Z(u_N) \leq z_N\} \quad (7)$$

Importantly, the set of sample values $\{z(u_1), \ldots, z(u_N)\}$ is viewed as one realisation of the random function. Just as the univariate cumulative frequency distribution of the random variable $Z(u)$ is applied to model the uncertainty about the value $z(u)$, the multivariate cumulative frequency distribution (Equation 7) is applied to model the uncertainty about the set of values $z(u_1), \ldots, z(u_N)$. Of particular interest in geostatistics is the bivariate, or two-point cumulative frequency distribution, of any two random variables $Z(u)$ and $Z(u')$ (Equation 8).

$$F(u, u'; z, z') = \text{Prob}\{Z(u) \leq z, Z(u') \leq z'\} = E\{I(u; z) \cdot I(u'; z')\} \quad (8)$$

When the joint distribution of two random variables is known it is possible to compute the univariate distribution of one random variable given the outcome of the second. The conditional cumulative frequency distribution $F(u;z | Z(u') \leq z')$ is the cumulative frequency distribution of $Z(u)$ given the knowledge of a joint random variable $Z(u') \leq z'$. Since the probability distribution is now conditional on the available data, the joint probability (Equation 8) is rescaled by the univariate probability of the known random variable (Equation 9).
\[
F(u; z \mid Z(u') \leq z') = \frac{\text{Prob} \{Z(u) \leq z \mid Z(u') \leq z'\}}{\text{Prob} \{Z(u') \leq z'\}}
\]
\[
= \frac{F(u; u'; z, z')}{F(u'; z')}
\]

The two random variables \(Z(u)\) and \(Z(u')\) are deemed independent when the conditional cumulative frequency distribution of each is equal to the cumulative frequency distribution at each location (Equation 10 and Equation 11).

\[
F(u; z \mid Z(u') \leq z') = F(u; z)
\]
\[
F(u'; z' \mid Z(u) \leq z) = F(u'; z')
\]

Substitution of the first independence condition (Equation 10) into the conditional cumulative frequency distribution expression above (Equation 9), defines the conditional cumulative frequency distribution as the product of the univariate cumulative frequency distribution of both random variables (Equation 12).

\[
F(u, u'; z, z') = F(u; z) \cdot F(u'; z')
\]

Rearranging this equation gives an expression for independence of the two random variables \(Z(u)\) and \(Z(u')\) (Equation 13).

\[
F(u, u'; z, z') - F(u; z) \cdot F(u'; z') = 0
\]

Applying the indicator transform of Equation 5, and the indicator representation of the two-point cumulative frequency distribution (Equation 8), the dependence of two indicator random variables \(I(u; z)\) and \(I(u'; z')\) is defined as an indicator cross covariance (Equation 14).

\[
C_i(u, u'; z, z') = \text{E}[I(u; z) \cdot I(u'; z')] - \text{E}[I(u; z)] \cdot \text{E}[I(u'; z')]
\]
The set of all indicator cross covariances \( C(u, u'; z, z') \) for all thresholds \( z, z' \), therefore measures the dependence between two random variables \( Z(u) \) and \( Z(u') \).

In contrast, the \( Z \)-two-point covariance \( C(u, u') \) measures the linear correlation between the two random variables (Equation 15).

\[
C(u, u') = E\{Z(u) \cdot Z(u')\} - E\{Z(u)\} \cdot E\{Z(u')\}
\] (15)

Both covariance terms are zero when the two random variables are independent. However, a zero covariance does not necessarily preclude dependence as the correlation can occur by a nonlinear relationship.

### 2.3 Stationarity

The cumulative frequency distribution (both univariate and bivariate) of a random function is location dependent and inference of the distribution requires repeated realisations of each random variable at each location \( u \). However, repeated measurements are never possible in situations of resource estimation when samples are usually only assayed once. To overcome this limitation, the random function is assumed to be stationary within \( \mathcal{A} \) whereby corresponding pairs of random variable at locations separated by a vector \( h \), \( \{(Z(u_\alpha), Z(u_\alpha + h); \alpha = 1, \ldots, n\} \) are assumed to be generated by the same probabilistic mechanism. The variable is therefore characterised by the same two-point distribution. The random function is strictly stationary when any two vectors of random variables \( \{Z(u_1), \ldots, Z(u_N)\} \) and \( \{Z(u_1 + h), \ldots, Z(u_N) + h\} \) have the same multivariate cumulative distribution function for all \( (u_1, \ldots, u_N) \) in \( \mathcal{A} \) (Equation 16).
\[
F(u_1, \ldots, u_N; z_1, \ldots, z_N) = F(u_1 + h, \ldots, u_N + h; z_1, \ldots, z_N)
\]
\forall u_1, \ldots, u_N \text{ and } h
\hspace{1cm} (16)

In practice, the assumption of stationarity is limited to the one and two point cumulative distribution functions and the mean and covariance of the random function. The reference to two locations of \( u \) is removed and the analysis is limited to the following relations.

- **One point cdf** : \( F(z) = \text{Prob}\{Z(u) \leq z\} \)
- **Two point cdf** : \( F(h; z, z') = \text{Prob}\{Z(u) \leq z, Z(u + h) \leq z'\} \)
- **Expected value** : \( m = E\{Z(u)\} \)
- **Covariance** : \( C(h) = E\{Z(u) \cdot Z(u + h)\} - E\{Z(u)\} \cdot E\{Z(u + h)\} \)
- **Variogram** : \( \gamma(h) = \text{Var}\{Z(u) - Z(u + h)\} = E\left\{\left[Z(u) - Z(u + h)\right]^2\right\} \)

The set of criteria for strict stationarity is rarely met in resource modelling and many earth science data sets. Geostatistical theory overcomes this problem by relaxing the stationarity requirements, such that only the expected value \( E\{Z(u)\} \) is considered invariant in \( A \) and the two-point covariance \( C(h) \) depends on only the separation vector \( h \). However, again many data sets do not meet this second order stationarity condition of a known mean, so an hypothesis of intrinsic stationarity is introduced whereby second order stationarity is only required for the increments \([Z(u) - Z(u + h)]\) of the random function.

The covariance function and the semivariogram of a stationary random function, where both exist, are related as shown in Equation 17.

\[
\gamma(h) = C(0) - C(h)
\]
\hspace{1cm} (17)
The correlation of two random variables $Z(u)$ and $Z(u + h)$ tends to zero as the separation distance $|h|$ increases (Equation 18)

$$C(h) \rightarrow 0 \text{ for } |h| \rightarrow \infty$$

(18)

The sill of a bounded semivariogram therefore tends towards the data variance $C(0)$ (Equation 19).

$$\gamma(h) \rightarrow C(0) \text{ for } |h| \rightarrow \infty$$

(19)

In some data sets, containing multiple populations or strong trends, second order stationary assumption may be limited to separate domains within the data region. However, the deterministic allocation of domains is often subjective in resource estimation and some trade off is required between better definition of model of rationalisation and the amount of available data.

2.4 Models of the random function

The first step in geostatistical resource estimation is to infer the type of random function and associated parameters from the available sample information in the study region. Despite the importance of the covariance function in defining the concepts of the random function, the principal diagnostic tool for quantifying the zone of influence of available attribute samples is the sample semivariogram [Matheron, 1963]. The sample semivariogram $\hat{\gamma}(h)$ is a measure of the average dissimilarity of pooled data pairs separated by a given vector $h$ (Equation 20).

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

(20)
Specifically, a semivariogram value is computed as half the average squared difference in magnitude of data-pairs which have been pooled into distance lags constrained by user selected angular and band-width tolerances [Deutsch and Journel, 1988].

In mineral deposits, the sample semivariogram of metal grade attributes is generally an increasing function of the distance \( h \), as on average, the farther samples are apart the greater the difference in metal concentrations. However, in practice, the computed semivariogram values for longer lag separations become increasingly unrepresentative because fewer data pairs are available to contribute to the computation, and/or data capture constraints introduce data that are not along the vector of interest.

The sample indicator semivariogram \( \hat{\gamma}_I(h; z_k) \) provides a measure of the range of continuity for a particular threshold of interest, \( z_k \) (Equation 21).

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

(21)

A series of indicator semivariograms can reveal how the continuity varies with changing threshold. Due to the binary coding, indicator semivariograms are less sensitive to extreme values and the near median thresholds often reveal patterns of spatial continuity when traditional semivariograms computed from the same input data are erratic. However, at extreme thresholds, the indicator semivariogram values tend to be more poorly structured than the median, particularly when there are few contributing data pairs.
Semivariograms are sensitive to preferential or clustered sampling, especially when combined with a changing variance across the study area that is related to the magnitude of local means - a phenomenon known as a proportional effect. If high grade (and associated high variance) areas are preferentially sampled in an area where a proportional effect exists, the semivariogram will tend to be overestimated for short lags. This overestimation can result in spatially unstructured or unexpected semivariogram shapes.

Matheron [1963] used the shape of the semivariogram near the origin to identify four classes of spatial continuity. Attributes with very high continuity produce a distinct parabolic trend at the origin. However, for mineral deposit metal grades, this type of behaviour is rare. A mean-square continuity is characterised by a linear trend at the origin. A discontinuity at the origin known as a nugget effect, marks highly variable behaviour at short range and is generally found along with the other patterns of spatial continuity due to sampling noise or lack of information at very short lags. The random, or "pure nugget effect" semivariogram, is the limiting case and indicates no correlation between sample pairs at any lag separation.

Semivariograms that reach a constant ‘sill’ value with increasing distance, such as that depicted on the left in Figure 2.1 are described as bounded. In many phenomena when the semivariogram value is scaled to the variance of the input data, the sill value is coincident with the data variance. When a sill structure exists, the ‘range’ of a semivariogram is defined as the pair separation distance at which the sill is reached. In instances where the sill value is not actually attained but approached asymptotically, a ‘practical range’ is defined as the distance at which the
semivariogram reaches 95% of the sill value. The range gives a quantitative measure of the geological concept of zone of influence of sample grades in mineral resource estimation. However, not all semivariogram calculations result in a sill, but such ‘unbounded’ semivariograms, as depicted in the right of Figure 2.1, are rare for metal grades in mineral deposits.

The sample, or experimental semivariogram, provides a set of results for a finite set of lags and directions. Geostatistical interpolation algorithms, such as those described in Section 2.5, require continuous functions to be fitted to the experimental values to allow estimation of the semivariogram values for all possible lags of \( h \). These estimates are expressed as a linear combinations of random variables \( Z(u) \) under the assumption that \( \{Z(u), u \in \mathcal{A}\} \) is a stationary random function with a covariance function \( C(h) \). The variance of the linear combination must be non-negative, a condition which is assured when the covariance model is positive definite (Equation 22).
Given the relation in Equation 17 (p. 27), the semivariogram model must therefore be negative definite.

To preclude testing the negative definiteness condition each time when modelling the experimental semivariogram, common practice involves using linear combinations of permissible functions that are known to meet the required criteria. The two negative definite models used in this thesis are as follows:

The nugget effect model is a step function that reaches the sill as soon as the range $h$ exceeds zero (Equation 23).

$$g(h) = \begin{cases} 
0 & \text{if } h = 0 \\
1 & \text{if } h > 0
\end{cases} \quad \text{(23)}$$

The spherical model is a piece-wise function that reaches a sill at the range $a$, $a > 0$ (Equation 24).

$$g(h) = \begin{cases} 
1.5 \cdot \frac{h}{a} - 0.5 \left(\frac{h}{a}\right)^3 & \text{if } 0 \leq h \leq a \\
1 & \text{if } h > a
\end{cases} \quad \text{(24)}$$

The nugget model applies to discontinuous behaviour and is generally combined with one or more other functions that model different behaviour at longer ranges.

When the spatial variability described by the semivariogram is the same for all directions in the same plane of reference, the phenomenon is said to be isotropic. For attributes characterised by bounded semivariograms, the spatial pattern of
variability is deemed anisotropic when the sill and/or the range of the modelled semivariogram changes with direction. Modelling anisotropy requires the generation of semivariogram functions dependent on a vector direction as well as distance. The description of anisotropy in two dimensions is outlined below; the three dimensional case is described in Isaaks and Srivastava [(1989) Chapter 16].

The type, axes directions and degree of anisotropy are identified through analysis of directional semivariograms. Typically, the data captured for each computation are limited in angular search and bandwidth to characterise how the semivariogram varies along a particular direction. Should the sill and range of the directional data be the same in all directions in the plane of investigation, the phenomenon is deemed isotropic. However, in mineral deposits, the continuity of metal grades generally varies with direction and the anisotropic character is revealed through directional analyses.

Initially, the axes of anisotropy can be interpreted through semivariogram surface contours or semivariogram rose diagrams [Isaaks and Srivastava, 1989, p.153 – 159]. Anisotropy is described as geometric when the directional semivariograms have the same shape and sill value in all directions, but the range varies with direction such that the plan plot of range values defines an ellipse in the two-dimensional case (or an ellipsoid for the three dimensional case). Figure 2.2 depicts the major and minor axis directional semivariograms for an example of geometric anisotropy.
In the case of anisotropy, a change of coordinates by means of a rotation and a
dilation is required to enable one to use the isotropic semivariogram model func­
tions previously specified. As a first step, a new set of axes is defined whose
directions coincide with the directions of greatest and least continuity respectively
(Figure 2.3, centre). The new axes may be thought of as having been obtained
from the original axes via a rotation in a clockwise direction by the angle $\theta$, meas­
ured from the y-axis.
The rotation is succeeded by a dilation by a factor of $\lambda = a_\phi / a_\theta < 1$. This step conceptually rescales the anisotropy ellipse to a circle with a radius equivalent to the minor axis range (Figure 2.3, right). However, it is important to note that the change of coordinates only affects the representations of the data locations, but not the actual data locations.

The coordinates after the rotation are given in equation 25

$$h_\theta = \begin{bmatrix} h_\phi \\ h_\theta \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} h_x \\ h_y \end{bmatrix}$$

and the final coordinates are as shown in Equation 26.

$$h' = \begin{bmatrix} h'_\phi \\ h'_\theta \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & \lambda \end{bmatrix} \begin{bmatrix} h_\phi \\ h_\theta \end{bmatrix}$$

The anisotropic semivariogram model $g^a(h)$ value for any given vector is then given by the isotropic semivariogram (Equation 27).

$$g^a(h) = g^i(|h'|) \text{ where } |h'| = \sqrt{h'_\phi^2 + h'_\theta^2}$$
Anisotropy is said to be zonal when the sill value varies with direction. This type of anisotropy is modelled as the sum of an isotropic bounded semivariogram $g_1(|h|)$ and a zonal structure $g_2(h_\phi)$ that does not contribute to the total semivariogram value in the direction of greatest continuity but is dependent on the direction of greatest variance (Equation 28 and Figure 2.4).

$$g(h) = g_1(|h|) + g_2(h_\phi)$$ (28)

Figure 2.4 Zonal anisotropy semivariograms and map

Modelling the zonal component essentially involves the same rotation and transformation as for geometric anisotropy but with an adaptation to an extreme case. The rotation transformation is the same as Equation 24, however the rescaling amounts to setting the range of $a_\theta$ to infinity which corresponds to an anisotropy factor $\lambda = a_\theta / a_\theta$ of zero (Equation 29).
Most natural phenomena require two or more models to fit the shape of the experimental semivariogram data. In the current research, nested models comprising a nugget and two or more spherical models are combined to model three-dimensional anisotropy. The objective of modelling is to capture the major spatial features of each attribute for both traditional and indicator semivariograms.

2.5 Estimation

The primary goal of mineral resource modelling is to estimate the volume and grade of a deposit from the available sampling information. With the advent of fast desktop computers, mineral resource grades are generally estimated along a grid of regularly spaced nodes that encompass the sampled volume. Attributes for metal grades and other variables of interest are assigned to each node in the grid as well as dimensional information for each block surrounding the node. Frequently, nodes to be estimated are constrained by three-dimensional tessellations that are constructed from the available data to define broadly stationary domains for separate estimation passes. In mineral resource models, these surfaces are usually grade and/or geological boundaries. This type of block modelling has largely replaced polygonal, sectional and contour methods of resource estimation [Annels, 1991].

Estimation of metal grade values for each model node from nearby samples requires the selection of an interpolation algorithm. All linear geostatistical interpolation algorithms are based on weighted linear combinations whereby different
weights are applied to the different samples in the neighbourhood of the unknown node [Isaaks and Srivastava, 1989].

2.6 Ordinary kriging

Kriging is a generic term that describes a set of least-squares regression algorithms that incorporate the patterns of spatial continuity as determined by modelling the experimental semivariogram. The following description of kriging theory is summarised from Goovaerts [1997, Chapter 5].

Estimation of a variable $Z$ at an unsampled location $u$ in a resource model (usually a grid node) using the $n$ sample data ($\{z(u_a), \alpha = 1, \ldots, n\}$) defines the estimation problem in terms of the key components of kriging equation. All kriging methods are variants of the basic linear regression estimator $Z^*(u)$ (Equation 30),

$$Z^*(u) - m(u) = \frac{1}{n(u)} \sum_{\alpha=1}^{n(u)} \lambda_\alpha(u) \cdot [Z(u_\alpha) - m(u_\alpha)]$$ (30)

The quantity $\lambda_\alpha(u)$, is the weight assigned to the data value $z(u_\alpha)$. Each $z(u_\alpha)$ is interpreted as a realisation of a random variable $Z(u_\alpha)$, and the terms $m(u)$ and $m(u_\alpha)$ are the expected values of the random variables $Z(u)$ and $Z(u_\alpha)$. The number of data used in the estimation may change with different locations in the model and in practice only the $n(u)$ data closest to the location $u$ being estimated. There is some subjectivity as to the number of data and size of the search neighbourhood used for each kriging estimate. However, methods exist to compute the theoretical regression slope for the kriging estimator to quantify the degree of bias in the estimate [Krige, 1997].
The random function $Z(u)$ in the kriging estimator is usually decomposed into a trend component $m(u)$ and random function residual component $R(u)$ (Equation 31).

$$Z(u) = R(u) + m(u) \quad (31)$$

The residual is modelled as stationary random function $u$ with zero mean (Equation 32) and covariance $C_R(h)$ (Equation 33).

$$E\{R(u)\} = 0 \quad (32)$$

$$\text{Cov}\{R(u), R(u + h)\} = E\{R(u) \cdot R(u + h)\} = C_R(h) \quad (33)$$

The expected value of the random variable $Z$ at location $u$ is therefore the value of the trend component (Equation 34).

$$E\{Z(u)\} = m(u) \quad (34)$$

The probabilistic interpretation that the value to be estimated $z(u)$ and the data values $z(u_o)$ are all realisations of random variables, $Z(u)$ and $Z(u_o)$, permits the definition of the estimation error random variable defined by $Z^*(u) - Z(u)$. The key objective in kriging is to minimise the estimation error variance $\sigma^2_E$ whilst maintaining an unbiased estimate. The unbiasedness condition is ensured when the average error is zero (Equation 35).

$$E\{Z^*(u) - Z(u)\} = 0 \quad (35)$$

The error variance is minimised under the constraint of unbiasedness by setting to zero the first partial derivatives with respect to weights of the error variance (Equation 36).
Ordinary Kriging (OK) is an adaptation of the basic kriging algorithm that accommodates local variations of the mean in the study region $A$ by limiting the stationarity conditions to a local neighbourhood $W(u)$ centred at the location $u$ being estimated. The local mean $m(u)$, which is unknown, is filtered from the linear estimator (Equation 30) by forcing the kriging weights to sum to one. The ordinary kriging estimator $Z^*_o(u)$ therefore becomes a linear combination of the $n(u)$ random variables $Z(u_a)$ (Equation 37).

$$Z^*_o(u) = \sum_{\alpha=1}^{n(u)} \lambda^o_\alpha(u) Z(u_\alpha) \quad \text{with} \quad \sum_{\alpha=1}^{n(u)} \lambda^o_\alpha(u) = 1$$

The $n(u)$ ordinary kriging weights $\lambda^o_\alpha$ are computed so as to minimise the error variance under the unbiasedness constraint. The ordinary kriging estimator is unbiased, as the mean of the error is theoretically zero (Equation 38).

$$E\{Z^*_o(u) - Z(u)\} = \sum_{\alpha=1}^{n(u)} \lambda^o_\alpha(u) m(u) - m(u) = m(u) - m(u)$$

$$= 0$$

The estimation error $Z^*_o(u) - Z(u)$ is viewed as a linear combination of $(n(u)+1)$ residual random variables $R(u)$ and $R(u_a)$ (Equation 39),

$$Z^*_o(u) - Z(u) = [Z^*_o(u) - m] - [Z(u) - m]$$

$$= \sum_{\alpha=1}^{n(u)} \lambda^o_\alpha(u) R(u_\alpha) - R(u)$$

$$= R^*_o(u) - R(u)$$
where,
\[ R(u_a) = Z(u_a) - m \]
\[ R(u) = Z(u) - m \]

The error variance is then a double linear combination of residual covariances (Equation 40).

\[
\sigma_E^2(u) = \sum_{\alpha=1}^{n(u)} \sum_{\beta=1}^{n(u)} \lambda_{\alpha}^{ok}(u) \lambda_{\beta}^{ok}(u) C_R(u_{\alpha} - u_{\beta}) + C_R(0) \\
- 2 \sum_{\alpha=1}^{n(u)} \lambda_{\alpha}^{ok}(u) C_R(u_{\alpha} - u) \tag{40}
\]

The minimisation of the error variance, subject to the constraint that the weights sum to one, requires the definition of a Lagrangian. This function (Equation 41) combines the error variance and the constraint that the weights sum to one, in one objective function using a Lagrangian multiplier that is required to be non zero to make the constraint active.

\[
L(\lambda_{\alpha}^{ok}(u), \alpha = 1, \ldots, n(u); 2\mu_{\alpha}(u)) = \sigma_E^2(u) + 2\mu_{\alpha}(u) \left[ \sum_{\alpha=1}^{n(u)} \lambda_{\alpha}^{ok}(u) - 1 \right] \tag{41}
\]

The kriging weights \( \lambda_{\alpha}^{ok}(u) \) are derived by setting the \( n(u)+1 \) first partial derivatives to zero (Equation 42 and Equation 43).

\[
\frac{1}{2} \frac{\partial L(u)}{\partial \lambda_{\alpha}^{ok}} = \sum_{\beta=1}^{n(u)} \lambda_{\beta}^{ok}(u) C_R(u_{\alpha} - u_{\beta}) - C_R(u_{\alpha} - u) + \mu_{\alpha}(u) = 0 \tag{42}
\]
\[ \alpha = 1, \ldots, n(u) \]

\[
\frac{1}{2} \frac{\partial L(u)}{\partial \mu_{\alpha}(u)} = \sum_{\beta=1}^{n(u)} \lambda_{\beta}^{ok}(u) - 1 = 0 \tag{43}
\]

The ordinary kriging system therefore comprises \( n(u)+1 \) linear equations with \( n(u)+1 \) unknowns, \( n(u) \) ordinary kriging weights \( \lambda_{\alpha}^{ok}(u) \) and a Lagrange multi-
plier $\mu_{ok}(u)$ that accounts for the unbiasedness constraint on the weights (Equation 44).

$$\begin{align*}
\sum_{\beta=1}^{n(u)} \lambda_{\beta}^{ok}(u) C_h(u_{\alpha} - u_{\beta}) + \mu_{ok}(u) &= C_h(u_{\alpha} - u) \\
\alpha &= 1,...,n(u) \\
\sum_{\beta=1}^{n(u)} \lambda_{\beta}^{ok}(u) &= 1
\end{align*}$$

(44)

The resulting minimum error variance of the kriging system is given in Equation 45.

$$\sigma_{ok}^2(u) = C(0) - \sum_{a=1}^{n(u)} \lambda_{a}^{ok}(u) C(u_{a} - u) - \mu_{ok}(u)$$

(45)

The ordinary kriging system can also be expressed in terms of semivariograms, as common practice is to model the semivariogram rather than the covariance function. However, for reasons of computational efficiency, kriging systems are usually solved in terms of covariances with modelled semivariograms converted by taking advantage of the relation $C(h) = C(0) - \gamma(h)$.

2.7 Indicator kriging

The outputs from ordinary kriging can provide a model of local uncertainty at an unsampled location $u$ by utilising the estimate and the error variance (kriging variance) under assumptions of Gaussian-type confidence intervals. However, the Gaussian assumption implies symmetry of the local error distribution, which is rarely achieved in practice. In addition, the derivation of confidence intervals implies the error variance is independent of data values, again a situation that is rarely met in practice when both high and low data values occur near locations to
be estimated. An alternative approach is to model the local uncertainty about the estimation location before deriving an optimal estimate that is appropriate to the problem at hand.

Ordinary indicator kriging is one non-parametric approach that does not assume any particular shape for the conditional distributions. The distribution function $F(u; z(n)) = \text{Prob}\{Z(u) \leq z(n)\}$ is made conditional on the available information $(n)$ and models the uncertainty such that probability intervals can be derived. In ordinary indicator kriging, the function $F(u; z(n))$ is modelled through a set of $K$ threshold values $Z_k$ that discretise the range of variation of the continuous attribute $z$ (Equation 46).

$$F(u; z_k | (n)) = \text{Prob}\{Z(u) \leq z_k | (n)\} \quad k = 1,\ldots,K$$  \hfill (46)

The $K$ conditional cumulative distribution function values are then interpolated within each class and beyond the upper and lower extremes. The conditional probability (Equation 48) is interpreted as the conditional expectation of an indicator random variable $I(u; z_k)$ given the information $(n)$ and conditional on adjacent data locations, where $I(u; z_k) = 1$ if $Z(u) \leq z_k$ and is otherwise zero.

The indicator method requires decisions as to the number and values of the thresholds. The selection criteria are subjective, but typically, critical cut-offs are selected with many thresholds (5 to 15) to discretise the local distribution on bands of approximately equal distribution frequency (such as deciles) or attribute concentrations. Extreme thresholds may be inappropriate when indicator semivariograms of higher cut-off grades are poorly defined because few pairs contribute to the semivariogram value. However, where extremes are of interest,
values can be extrapolated from the continuity trends derived from intermediate
thresholds, or from the better structure of semivariograms on more closely sam­
piled directions of anisotropy.

The general kriging estimator can be adapted to the problem of estimating an
indicator value \( i(u; z_k) \) at any location \( u \) using measurements of the attribute of
interest defined at the threshold \( z_k \) (Equation 47).

\[
[I(u; z_k)]^* - E[I(u; z_k)] = \sum_{a=1}^{n(u)} \lambda_a(u; z_k) [i(u_a; z_k) - E[i(u_a; z_k)]]
\]  

(47)

The quantity \( \lambda_a(u; z_k) \) is the weight assigned to the indicator \( i(u_a; z_k) \) that is inter­
preted as the realisation of a random variable \( I(u_a; z_k) \). Like ordinary kriging,
ordinary indicator kriging accommodates local fluctuations of the indicator mean
by limiting conditions of stationarity to a local neighbourhood \( W(u) \). The ordi­
nary indicator kriging estimator is a linear combination of the \( n(u) \) indicator ran­
dom variables \( I(u_a; z_k) \) in \( W(u) \) (Equation 48) where the weights are determined by
the ordinary kriging system.

\[
[F(u; z_k | (n))]^* = \sum_{a=1}^{n(u)} \lambda_a(u; z_k) I(u_a; z_k)
\]  

(48)

The outputs from indicator kriging are conditional cumulative distribution func­
tions at each model node that are compiled from estimates of the probability of
exceeding each given threshold \( z_k \). Each posterior probability must lie in the
interval \([0,1]\) and the sequence of \( K \) estimates must be a non-decreasing function
of the threshold value \( z_k \). These two order relationships are often not satisfied,
predominantly due to the lack of \( z \)-data in some threshold classes and/or changing
variogram parameters with changing thresholds. Fortunately, in practice, the magnitude of order deviations is small and can be filtered out of the conditional cumulative distribution function by averaging bin-adjacent probability values in an upward and downward sequence as described in Deutsch and Journel [1998].

The coarse resolution of the posterior conditional cumulative distribution function outputs of ordinary indicator kriging can be improved by interpolation between class boundaries and by extrapolation of the lower tail (below the lowest threshold \( z_1 \)) and the upper tail (above the largest threshold \( z_K \)). Typically, linear interpolation is applied between thresholds and, for skewed distributions, power or hyperbolic models are applied to the extrapolated tails [Deutsch and Journel, 1998]. Cumulative frequency plots of input sample data can be used as guides to which of the available functions give an appropriate fit to the tails of the distribution. However, in practice, grade smoothing during estimation results in tail shapes that are different from those of the input distribution and some subjectivity is required in selecting the parameters for the tail functions.

A conditional cumulative distribution function model of an unknown attribute \( z(u) \) at location \( u \) permits easy assessment of uncertainty. However, many mine-planners do not think in terms of probability, so the measure of uncertainty is typically replaced by an estimate \( z^* (u) \). A common output is the expected value, of the local distribution called the E-type estimate (Equation 49)

\[
 z^*_K (u) = \int_{-\infty}^{\infty} z \, dF(u; z \mid (n)) \approx \sum_{k=1}^{K+1} z_k \left[ F(u; z_K \mid (n)) - F(u; z_{K-1} \mid (n)) \right]
\]

(49)

where \( z_k, k = 1, \ldots, K \) are the \( K \) thresholds retained. The conditional mean value \( z^*_k \) within each class, \( (z_{k-1}, z_k) \), is obtained from interpolation methods as described
in Deutsch and Journel [1998]. Typically, a linear interpolation is used between specified thresholds and hyperbolic, or power models, are used to extrapolate the conditional mean above the maximum cut off and below the minimum cut off to user specified minimum and maximum values. The user minimum and maximum values can be determined from the input data and problem-specific knowledge of the likely attribute range.
The issues of mineral resource estimation that motivated this thesis are discussed in this chapter as well as the hypotheses tested in an attempt to resolve these issues. The general approach taken is to investigate two different sampling patterns and two estimation methods applicable to nickel laterite deposits, with the aim of determining the optimum resource estimate from the wide-spaced sample information available at the exploration stage. Comparing estimates derived from exploration data to values derived from more detailed mine-scale sampling tests the quantification of an optimum resource model. This type of comparison is known in the mining industry as reconciliation [Lewis, 1987]. However, in terms of ultimate financial evaluation of a deposit, several aspects of exploitation of nickel laterite deposits need to be considered in parallel to reconciliation results.

Mining expenditure is a minor cost consideration for nickel laterite deposits in comparison to ore processing costs. More critical to the economic evaluation of a deposit is the estimation of the amount of high grade mineralisation available for exploitation in early development years. However, the close-spaced sampling that is required to locate pockets of high grade mineralisation, and the additional sampling costs, are generally considered unreasonable at the exploration stage. Rather than an intensive sampling methodology, the preferred exploration approach is sequential campaigns of wide-spaced sampling to define the global deposit volume, followed up by local intensive sampling programs to determine the character of the grade-tonnage distribution.
However, this exploration sampling approach invokes several estimation issues that are significant not only for nickel laterite deposits, but also for many tabular mineral deposits. In particular, the effectiveness of local sampling patterns are subject to design and stationarity assumptions, and particular combinations of deposit geometry and sampling configuration result in inappropriate estimates, despite correct theoretical approaches to grade interpolation. Proposed solutions to these problems, with respect to nickel laterite deposits, are discussed below.

3.1 Sampling optimisation

The major exploration expenditures on nickel laterites relate to sampling with the cost accruing from drilling, analytical assaying, supervision and compilation of the results. The total expenditure is therefore a function of the horizontal plane drillhole spacing and downhole sample length. Whilst a management goal is to minimise the total cost, by using the widest spaced pattern and longest composite length practicable, the cost of this approach must be weighed against the degree of uncertainty that is acceptable in the resource model. The cost benefit of close-spaced exploration sampling can be gauged by the improvement in accuracy of the grade of interest in the resource model derived from denser sampling against the additional cost of sampling. Less easy to quantify is the opportunity cost of the extra time required to define the mineral resources to a higher degree of spatial accuracy. The choice between accuracy and speed of definition is a risk-based management decision. This risk can be minimised by the use of estimation methods that are appropriate for the sample spacing and character of the available data.
The sampling methods used to define resources in mineral deposits have advanced significantly over time, due to technical improvements in drilling and analytical methods. However, there has been little change in terms of drillhole pattern and density. As a general approach, deposits are initially tested by regular patterns of wide-spaced drill holes with the aim of defining the limits of mineralisation and locating the highest economic grade zones of the deposit. When the results from the initial campaign are received, in-fill drilling is then completed on more closely spaced patterns, often concentrating on high grade zones interpreted from the initial pattern. Frequently, the latter stages of evaluation involve clusters of close-spaced drill holes to test the short-range continuity of the attributes of interest.

In terms of geostatistical resource estimation, the accuracy of the estimate depends mainly on the sampling pattern and the behaviour of the semivariogram [Chiles et.al., 1996]. Whilst regular spaced patterns resolve issues of clustered sampling and result in theoretically superior estimates [Olea, 1999], initial campaigns of exploration drilling in nickel laterites typically occur at drill hole spacings greater than, or near to, the range of the horizontal plane semivariograms. Moreover, the short ranges of key attributes in nickel laterite deposits, as shown in the examples in Chapter 5, dictate that detailed regular sampling and accurate location of high grade ore is only cost-feasible immediately prior to mining. However, to quantify short-range continuity at the exploration stage, short-range information about the semivariogram is determined from complementary patterns added to the regular wide-spaced grid. Chilès, Bourgine and Niandou [1994] tested the effectiveness of a variety of complementary in-fill patterns used to determine the short-range character of the
semivariogram. They concluded that in the presence of true stationarity, the location of the pattern is not important and that a single cross pattern or compact cluster pattern is the most efficient approach to define the deposit semivariogram. However, after testing a variety of short range patterns on simulated data from a nickel laterite deposit, they concluded that when a regionalisation of nickel grades is not strictly homogeneous, either an in-fill cross of holes needs to be situated at a 'deposit-representative' location or a pattern of several small crosses should be used to quantify short-range continuity. The latter approach is more logical since the selection of a representative location is problematic when the character of the deposit is not known before planning sampling programmes.

Following this line of reasoning, the variography and resulting estimates from two sampling patterns are compared in this thesis. The first pattern is the actual exploration pattern of the deposit comprising a regularly spaced sampling pattern with one local cluster of drill holes. The second, alternative pattern contains wide-spaced and close-spaced holes designed on a stratified sampling approach. There are 20% fewer samples in the alternative pattern compared to the actual exploration pattern resulting in substantial cost savings. More detail is given in Chapter 4.

3.2 Resource geometry and interpolation

Even with dense sampling grids and good definition of the histogram and semivariogram, estimation methods are influenced by undulating or folded deposit geometry. Problems of counter-intuitive estimation results for deposits within folded strata have previously been recognised [Dagbert et.al., 1984; McArthur
1998; Annels et al., 1994]. However, in researching this thesis the writer could not find any published application of unfolding methods for nickel laterites, as most published work concentrated on strata that are structurally folded rather than undulating in regoliths. These estimation issues for undulating deposits are explained below with reference to the schematic illustration in Figure 3.1.

In Figure 3.1, a resource envelope is depicted representing a limiting grade threshold of economic interest. The background grid centroids represent point estimates at regular locations within the resource model. The resource envelope selection and drillhole grades are somewhat idealised but the scale and geometry is representative of a typical nickel laterite deposit as detailed in Chapter 4. A dashed line representing a surface of interpreted grade connectivity (as inferred from geological processes) is also depicted.

Resource estimation modelling and grade interpolation algorithms require the definition of a local sample search neighbourhood for each estimate. Due to the
strong vertical anisotropy of nickel laterite deposits and the global horizontal
orientation of the mineralised blanket, the neighbourhoods can be considered as
thin horizontal ellipsoids, again depicted for two nodes in Figure 3.1.

When the ellipsoidal search window is moved from node to node during grade
estimation, the combination of undulating deposit shape and sample location
results in counter-intuitive estimates at some nodes. Each estimated grid cell
within the resource envelope in Figure 3.1 has been colour shaded to represent the
grades estimated from drill hole samples captured within the ellipsoidal search
window. With this ‘hard-boundary’ style of interpretation, the ‘waste’ samples
outside the constraining envelope are flagged as non-existent and are not used in
grade interpolation.

The estimated grades are more smoothly distributed than the sample grades due to
the averaging effects of the interpolation algorithm. Figure 3.1 serves to illustrate
the two major artefacts that result from this common interpolation configuration.
These are:

1. The hard boundary constraint results in an abrupt change in the modelled
   block grade at the boundary that may not be consistent with the geological
   processes that have formed the deposit (see Block A in Figure 3.1). In
   some mineral deposits where interfingering or adjacent barren geological
   units occurs, a hard boundary may occur. However, for a nickel laterite
deposit formed by percolation and precipitation of metal-rich solutions
   through the regolith, this model is unrealistic. The hard boundary is more
an interpolation requirement to exclude low-grade samples from the search window than a method to model the inferred geological continuity.

2. The spatial distribution of interpolated grades does not match the expected geological continuity. This artefact results from the requirement that the search ellipse be oriented horizontally to match the global geometry of the deposit. On a local scale, the horizontal search only reproduces the expected grade connectivity where the geometry is inferred to be horizontal from adjacent drill holes (e.g. Block B in Figure 3.1). The more frequent case is that there is some local inclination between sample strings and the search ellipse results in horizontal banding of metal grades (Block C, Figure 3.1). This type of artefact is resolved when denser sampling is available (block D Figure 3.1). However, as stated previously, the extra sampling cost may be significant and preferably postponed to the mining stage.

These problems of geometric controls impacting on the grade estimation of folded or undulated geometry have been recognised by several authors. The methods that have been proposed to address these problems fall into five categories.

1. Subdividing the deposit into zones of similar orientation [Wellmer & Giroux, 1980]. This solution works well for some deposit styles but is unrealistic for the multitude of domains that would be required to accommodate nickel laterite geometry.

2. Reducing the problem to a two-dimensional plan through interpolation of metal accumulations and seam thicknesses [Journel and Huijbregts, 1978].
This method requires a prior interpretation of economic grade thresholds and the definition of grade zonation in the vertical dimension is lost. In addition, interpolating the enveloping surfaces of mineralisation can produce further artefacts such as negative thicknesses [Dowd, Johnstone & Bower, 1986].

3. *Replacement of Euclidean coordinates by local stratigraphic coordinate systems* [Sides and da Silva, 1994; Dagbert et.al., 1984; McArthur, 1988; Annels et.al., 1994; Deutsch, 1999; Barrett, 2000; Lambert, 2000]. These more complex methods utilise reference surfaces or shapes to determine relative stratigraphic coordinates for both the sample data and the locations to be estimated. The impact is to effectively distort the geometry of the search neighbourhood to match the interpreted geological structure. However, when more than one unfolding system is required to accommodate different surfaces of connectivity for the same domain, the process becomes tedious.

4. *Breaking the data down into stratigraphic domains and estimating each in isolation* [Murphy, 1998]. This method results in artefacts at domain boundaries due to the different data captured in the search neighbourhood immediately either side of the boundary.

5. *Vertical translation of data and panel centres with respect to a reference surface* [Sahin et.al., 1998]. This method involves some space contraction of Euclidean distances in the horizontal plane but the error is minor for widely spaced data and gently undulating surfaces.
The last method of correction is tested in the current research due to ease of implementation and transparency of results. The unfolding methodology is depicted schematically in Figure 3.2.

As depicted in Figure 3.2, the unfolding and unfolding estimation involves a four-step process. These steps are:

1. Interpretation of a resource envelope and unfolding reference surface of expected geological grade continuity from the sampling data within the area of interest.

2. Vertical translation of the data, the envelope, and the block model nodes to unfolded space. The process is achieved by simply subtracting the eleva-
tion of the reference surface from the elevation coordinates of each element. A constant is added back to each elevation coordinate to preclude negative elevations. At this stage, semivariograms can be computed for the unfolded coordinates.

3. Estimation of grades at node locations in unfolded space to enhance connectivity using unfolded variography

4. Translation of estimates back into in situ space.

In this thesis, the data manipulation and unfolding was carried out using utilities in MineMap software [MineMap, 2001]. The same capability can be implemented in a number of mining based software packages.

The issues of interpolation and deposit geometry are further exacerbated in kriging-based estimates. Deutsch [1993] identified and documented the problem of the screening effect of kriging on geostatistical resource estimates. Essentially, when samples are collected as strings of data, kriging systems compute inappropriate weights for samples that are clipped to a finite domain. This finite domain results from the limits of the search neighbourhood or some hard boundary constraint imposed during resource modelling. The problem, known as the drill core paradox [Shurtz, 1995], is depicted schematically in Figure 3.2.
When sample strings are inside the range of the semivariogram, the kriging weights at the limits of the search envelope are computed as higher values than those at the centre of the drill string. When there is zonation in the deposit such as depicted in the drill hole sample string, the effect is such that the higher-grade values are given lower weights than the more marginal material. The effect of inappropriate weights is reduced for samples located at distances at and beyond the range of the semivariogram and/or semivariograms characterised by high nugget effects. In these situations, the kriging weights are close to equal.

Unfortunately, the only solution to this problem in three-dimensional estimation for closer samples is a modification of the kriging system that results in the loss of the accuracy of the kriging estimate at sample locations [Deutsch, 1994]. This method has not been tested in the current research, however, the use of octant search methods and limiting the number of samples captured in each octant of the search neighbourhood have been applied to minimise the impact of inappropriate kriging weights applied to the samples at the margins of sample strings.
3.3 Research hypotheses and testing

There are three hypotheses considered in this thesis. Firstly, the use of the unfolding method during estimation as depicted in Figure 3.2 is expected to give a better definition of the volume of high grade nickel and cobalt mineralisation than comparative in situ estimates. An assumption here is an unfolding surface interpreted on the basis nickel-cobalt grade continuity is assumed applicable to both elements.

The second hypothesis is that a cost saving alternative sampling approach that is based on a stratified sampling pattern gives a comparable estimate to the more regular and more closely spaced sampling pattern of the actual exploration-sampling pattern used on the MM2 deposit that is described in Chapter 4. Thirdly, that indicator kriging estimates are expected to further improve definition of the volume of high grade mineralisation in comparison to ordinary kriging estimates derived from the sampling configuration.

Specific conjectures considered are as follows:

1. Unfolding by vertical translation improves the connectivity of high grade nickel and cobalt zones in the deposit, as would be expected from the geological understanding of deposit formation. This improved connectivity is recognised by improvements in unfolded variography compared to the in situ case.

2. Grade interpolation in unfolded space, utilising unfolded variography, better predicts the deposit grade volume relationships.
3. The alternative sampling pattern of several local clusters gives better definition of short-range spatial continuity than one local cluster. The idea here is that the deposit may not be strictly homogeneous and a stratified pattern containing several local clusters will give a better representation of the short-range behaviour.

4. Indicator kriging estimation methods return more realistic estimates than ordinary kriging estimates, due to the ability of indicator kriging to model a range of grade thresholds. This improvement should be apparent for both in situ and unfolded cases and for the standard and stratified patterns.

The balance between optimum sampling, degree of risk and speed of production of the resource model is best determined by comparing the resource model predictions to actual production [Journel and Huijbregts, 1978, p.4]. At the mining stage, the 'grade control' sample spacing is much closer, the geology is better understood, and detailed comparisons can be made. Therefore, to test the hypotheses listed above, the results from testing are compared to detailed information available from grade control sampling. The approach to establishing the input sample data sets has been to resample the detailed grade control sampling to create the two input sampling configurations and carry out ordinary kriging and indicator kriging estimates in parallel in order to quantify how well each hypothesis performs.

Specifically, different variography and estimates are compared for:

(i.) ordinary kriging in situ (without unfolding)

(ii.) ordinary kriging unfolded;
(iii.) indicator kriging in situ,

(iv.) indicator kriging unfolded,

which are carried out for:

(i.) the actual exploration pattern used to define the deposit, and

(ii.) an alternative exploration pattern of stratified design.

The extracted datasets are described in Chapter 4. Variography results are outlined in Chapter 5 and estimation results in Chapter 6. Chapter 7 discusses the results and conclusions are drawn with respect to the tested hypotheses.
4 THE MM2 DATASET

Anaconda Nickel Limited provided a nickel laterite dataset for use in this thesis. The dataset is a subset of exploration and mine samples from an area within the MM2 deposit at the Murrin Murrin nickel-cobalt mine in Western Australia. Anaconda has requested that the exact geographic coordinates and detailed geological character of the data be kept confidential. In keeping with this request, the original data have been translated and rotated to a local coordinate system and the following descriptions focus on the sample quality, spatial description and statistical character of each sample set.

4.1 Sample collection

The MM2 samples used in this study were originally collected as metre long composites from reverse-circulation percussion (RCP) or reverse circulation air-core (RCA) drilling. In dry ground conditions, both drilling methods eliminate cross-contamination of adjacent samples by capturing the drill cuttings at the face of the advancing drill string and transporting the sample to the surface via an inner tube; as depicted on the left hand side of Figure 4.1.

The differences between the two drilling methods relate to the mechanics of the sample collection from the advancing drill string. The sample from RCP is pulverised at the drill face, whilst the RCA sample is drilled as a whole-core, and then crushed on return to the sample cyclone (Figure 4.1). However, as both sample types collected were of similar (large) volume and recovery, and the concentrations of the elements of interest are relatively high, the statistical support (in terms of volume variance) of each type can be considered near identical. The
equivalence of the exploration and mine sampling methodologies therefore removes the change-of-support issues often associated when reconciling resource definition estimates to mine production or grade control estimates, such as those described by Humphreys and Shrivastava [1997].

![Sample collection flow sheet for the MM2 study area.](image)

The collar positions of all drill holes were accurately surveyed, however, no downhole surveys of drill paths were taken. Downhole surveys were deemed unnecessary as the drill holes are shallow vertical holes (generally less than 30 metres depth) that are drilled in a comparatively soft weathering profile. As such, no significant path deviation was expected (as opposed to drilling in hard rock).

For each one-metre sample composite collected in the study area, approximately 20 to 30 kilograms of cuttings were retrieved over the one metre sample interval.
The total mass of material collected is largely dependent on the in situ bulk density of the material in the weathering profile. Each large composite was then reduced to a two to three kilogram sub-sample by pouring the entire sample through a riffle splitter (Figure 4.1). The sub-samples were then assigned a unique sample number and dispatched to a reputable commercial laboratory where the samples were analysed for a suite of elements. Anaconda also carried out systematic duplicate assays every 20th sample to monitor the accuracy of the sampling and analytical results.

4.2 Sampling patterns

Several campaigns of drilling and sampling have been carried out over the MM2 study area. RCP drilling was used primarily on early wide-spaced patterns for resource definition work whilst RCA was utilised for the more intensive mine sampling known as grade control. For the purposes of this thesis, the data selection has be limited to those drillholes occurring within the extents of a preliminary open cut mine into the MM2 deposit.

4.2.1 Actual exploration sampling pattern

The actual exploration pattern of drill holes, depicted in Figure 4.2, is the culmination of several phases of sampling prior to mine development.
The initial phase of drilling was designed to locate the boundaries of the deposit. Accordingly, all holes were targeted to penetrate the full thickness of the nickel-cobalt mineralisation, with each hole being terminated on the instructions of a geologist. The base of the mineralised profile was determined from the visible mineralogy of drill cuttings.

Later, an infill drill pattern targeted the higher nickel grade portions of the resource on a 50 metre square in-fill pattern. In addition to the square in-fill pattern, a 25 hole cluster and a line of nine, 12.5 metre spaced holes were drilled to gather data on the short-range continuity within the study area.
4.2.2 *Grade control sampling pattern*

The grade control drilling over the MM2 study area was completed on a 12.5 metre square pattern. The grade control pattern incorporates the prior exploration drilling (Figure 4.3).

Most of the grade control drilling was completed following a phase of surface waste removal. The depth of the waste was determined from the initial exploration sampling results at a cut off grade. Importantly, the grade control sampling used in this thesis did not penetrate the full depth of the mineralised profile because of the intention to only sample within the bounds of the preliminary open pit.

Several restrictions have been placed on both the exploration and grade control data sets for the purposes of this thesis. These are as follows.
1. Both data sets have been truncated at approximately 30 metres depth below the ground surface (922 mZ); this depth represents the approximate base of grade control drilling.

2. The original one-metre samples have been accumulated into two metre, mining bench-height composites through the open pit area, as detailed in section 4.3.1.

3. A three-dimensional mineralisation boundary has been interpreted from the grade control data to exclude waste-grade domains that occur predominantly near the surface as described in section 4.3.2.

Figure 4.4 below shows a vertically exaggerated (2:1) west to east profile through section 250 mN (metres north). Bench-height composites are colour coded for nickel on the top profile and cobalt in the lower profile of Figure 4.4. The selected waste boundary is depicted in red and the grade control holes can be distinguished by the deeper collar locations on the profiles.

The grade control data reveal the undulating nature of the higher grade (>1.0% Ni) part of the nickel blanket. The connectivity of high grade cobalt (>0.10% Co)
less pronounced as nickel, but generally matches the undulating path of high grade nickel within the resource envelope.

### 4.2.3 Alternative exploration sampling pattern

One of the aims of this thesis is to test a sampling configuration that may be more cost effective than the original exploration pattern. The effectiveness of the alternative pattern can be evaluated in terms of not only financial savings and opportunity costs (that is, the opportunity to spend the cost saving elsewhere for benefit), but also on improvements in quality of information. An alternative exploration sampling pattern was sampled from the grade control pattern to produce the collar configuration shown in Figure 4.5. The design of the alternative exploration pattern was based on stratified sampling designed as described by Chiles et.al. [1996] and is described below.

![Figure 4.5 Alternative exploration drill hole pattern.](image-url)
This alternative exploration pattern has a design emphasising the collection of globally representative short scale information at the expense of less intensive wide-spaced regular sampling. The first phase of sampling is a wide-spaced pattern that defines the limits of the mineralised zone. From geological inferences, the strike direction of longest continuity is interpreted to be east to west. Accordingly, the first pass pattern is a rectangular grid with a 100 metre north and a 200 metre east separation distance. The second pass of sampling comprises infill holes spaced at 50 metres on the cross-strike, north-south lines. Along strike, the pattern is extended to 100 metre spaced diamond patterns in anticipation of greater grade continuity.

Finally, several sets of 12.5 metre spaced crosses are drilled to gather short-range data. These crosses are drilled on a staggered pattern of approximately 200 metres north by 400 metres east. The alternative sampling pattern represents a 20% cost saving in terms of drilling and sampling when compared to the actual exploration sampling pattern.

4.3 Data manipulation and interpretation

Prior to estimation of grades from the various sampling patterns, the original data were manipulated and interpreted by the writer to facilitate testing of conjectures described in section 3.3.

4.3.1 Bench height composites

As mining of the deposit was completed over two metre bench heights, the one metre sample data were accumulated into a two metre composite that is coincident with the two metre height of the mining benches. This process involves splitting
the one metre samples at the mining bench ‘toe’, then accumulating the contained samples by length weighting the grade over the bench height (Figure 4.6).

The bench composite $z(u_a)$ is a length weighted composite grade computed from $n$ composites and partial composites of length $l_d$ and metal grade $z(u_{ad})$ (Equation 50).

$$z(u_a) = \frac{\sum_{d=1}^{n} z(u_{ad}) \cdot l_d}{\sum_{d=1}^{n} l_d}$$

This process creates a few residual samples of less than two metres in length near the topographic surface and at the ends of some holes. However, the majority of these residuals are excluded from further analysis by clipping of the data sets following interpretation of a resource envelope.
4.3.2 Resource envelope interpretation

From the two metre bench-height composites of the grade control data, a constraining envelope was applied to exclude waste materials and the zone of incomplete detailed sampling in the deeper part of the deposit. As both nickel and cobalt have economic value, a nickel-equivalent (NiEq) service variable was calculated for each composite by the simple formula (Equation 51)

\[
\text{NiEq} \% = \text{Ni} \% + 4.5 \times \text{Co} \%
\]  

(51)

A threshold of 0.4% NiEq was selected as a minimum level of value-metal concentration for inclusion of bench composites in the resource envelope. This concentration is marginally below the grade required for ore processing and is a level that excludes areas of definite waste from the resource envelope. Whilst comparable studies of nickel laterite resources have been carried out without grade constraints [Journel and Huijbregts, 1978], imposing a grade boundary helps reduce the issues of inappropriate kriging weights that occur when dealing with linear strings of data [Deutsch, 1994].

In addition to a grade cut off, the available data in each sample configuration were truncated at 922 m elevation. This limit ensured correspondence of data limits for all sampling patterns.

With the grade threshold and depth constraints determined, a resource envelope polygon was digitised on a PC-screen for each east-west drill section of each grid configuration of the grade control sampling. The same boundary resource envelope was then applied to the two exploration sampling configurations.
4.3.3 Unfolding surfaces

Lines of connectivity for high grade mineralisation were interpreted for each of the drill sections of the exploration sampling configurations. Essentially, the interpretation involved a linear connection of the high grade nickel equivalent values in adjacent drill holes on each section. These lines were then triangulated to form the reference surface for vertical translation of data in the unfolded estimates.

4.4 Univariate Statistics

Nickel clustered and declustered summary statistics for the two metre bench composites were extracted from the resource envelope for each sampling configuration and are compared in Table 4.1. Declustered statistics were computed for the exploration sampling patterns using cell delcustering (25 metre square) in the GSLIB, DECLUS program to account for the local sampling clusters that occur in the exploration sampling patterns.

<table>
<thead>
<tr>
<th>Nickel Statistic</th>
<th>Grade Control</th>
<th>Actual Exploration</th>
<th>Alternative Exploration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clustered</td>
<td>Declustered</td>
<td>Clustered</td>
</tr>
<tr>
<td>Composites</td>
<td>13414</td>
<td>1046 1046</td>
<td>838 838</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.07</td>
<td>0.13 0.13</td>
<td>0.15 0.15</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.67</td>
<td>2.23 2.23</td>
<td>2.23 2.23</td>
</tr>
<tr>
<td>Range</td>
<td>2.61</td>
<td>2.09 2.09</td>
<td>2.08 2.08</td>
</tr>
<tr>
<td>Mean</td>
<td>0.85</td>
<td>0.84 0.80</td>
<td>0.83 0.79</td>
</tr>
<tr>
<td>Median</td>
<td>0.81</td>
<td>0.80 0.75</td>
<td>0.78 0.73</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.38</td>
<td>0.39 0.38</td>
<td>0.38 0.38</td>
</tr>
<tr>
<td>Variance</td>
<td>0.14</td>
<td>0.15 0.14</td>
<td>0.15 0.14</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>0.44</td>
<td>0.46 0.47</td>
<td>0.46 0.48</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.49</td>
<td>0.59 0.64</td>
<td>0.79 0.83</td>
</tr>
</tbody>
</table>
Prior to and following delcustering, the statistics of both exploration patterns are similar. The skewness of the alternative exploration pattern stands out as being higher than the parent grade control dataset. Similar comparative statistics for the cobalt samples inside the resource envelope are listed in Table 4.2.

<table>
<thead>
<tr>
<th>Nickel Statistic</th>
<th>Grade Control</th>
<th>Actual Exploration</th>
<th>Alternative Exploration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Clustered</td>
<td>Declustered</td>
</tr>
<tr>
<td></td>
<td>Clustered</td>
<td>Declustered</td>
<td></td>
</tr>
<tr>
<td>Composites</td>
<td>13411</td>
<td>1046 1046</td>
<td>838 838</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.001</td>
<td>0.001 0.001</td>
<td>0.004 0.004</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.887</td>
<td>0.887 0.887</td>
<td>0.587 0.587</td>
</tr>
<tr>
<td>Range</td>
<td>0.886</td>
<td>0.886 0.886</td>
<td>0.583 0.583</td>
</tr>
<tr>
<td>Mean</td>
<td>0.058</td>
<td>0.054 0.053</td>
<td>0.054 0.051</td>
</tr>
<tr>
<td>Median</td>
<td>0.040</td>
<td>0.038 0.036</td>
<td>0.039 0.037</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.054</td>
<td>0.054 0.056</td>
<td>0.050 0.048</td>
</tr>
<tr>
<td>Variance</td>
<td>0.003</td>
<td>0.003 0.003</td>
<td>0.002 0.002</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>0.944</td>
<td>0.993 1.053</td>
<td>0.929 0.930</td>
</tr>
<tr>
<td>Skewness</td>
<td>3.560</td>
<td>5.495 6.686</td>
<td>3.456 3.600</td>
</tr>
</tbody>
</table>

Similar to the nickel statistics comparisons, declustering results in decreases of means and medians and increases in the coefficient of variations and skewness. The statistics of the alternative exploration pattern understate those of the parent grade control data, as the maximum data value was not captured. The exploration pattern statistics are much closer to the underlying grade control data, however the coefficients of variation and skewness are overstated.

The Q-Q plots in Figure 4.7 compare the declustered quantiles of the exploration sampling patterns to the declustered quantiles of the grade control pattern. These plots reveal that there is little bias between the source grade control pattern distributions and the two declustered distributions of the exploration patterns.
ever, some bias is apparent in the high grade part of the histogram. This high grade bias is more pronounced for cobalt than nickel.

![Figure 4.7 Nickel and cobalt Q-Q plots, exploration versus grade control pattern](image)

Differences in histogram shape are more apparent in Figure 4.8, which shows the histograms and cumulative frequency graphs for nickel and cobalt for each of the sampling configurations.
In summary, the statistics of the exploration configurations successfully capture the univariate character of the parent grade control set. Following declustering, both exploration distributions are largely unbiased with respect to the grade control data but with some degree of under representation of higher grade values of nickel and cobalt.
5 VARIOGRAPHY

The grade continuity and anisotropy for each sampling configuration was investigated through traditional and indicator variography using GSLIB VARMAP and GAMV programs [Deutsch and Journel, 1998]. The results for each sampling configuration, including unfolded versions of the exploration and alternative exploration sampling patterns, are compiled in Appendix A and Appendix B for nickel and cobalt respectively. The convention for direction that has been used in all analyses is the geological convention where north is zero degrees and east is 90 degrees.

5.1 Indicator thresholds and semivariogram computational methods

Twelve indicator thresholds were selected using an approach of equal increments of metal grade to discretise the local distribution of each element. The same thresholds were applied to each data configuration. Equal metal increments were selected rather than percentile increments, as certain concentrations have particular significance both in terms of resource reporting and cost analyses. This approach allows comparing results from each sampling configuration in terms of these key thresholds. Adoption of an equal metal scheme of thresholds also results in adequate discretisation of the critical parts of the histogram, as recommended by some practitioners [Vann et.al. 2000]. The selected indicator thresholds for each sampling configuration are listed in Table 5.1 for nickel and Table 5.2 for cobalt.
**Table 5.1**

Nickel indicator thresholds and percentiles

<table>
<thead>
<tr>
<th>Indicator Bin</th>
<th>Threshold Ni%</th>
<th>Grade Control</th>
<th>Actual Exploration</th>
<th>Alternative Exploration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>27%</td>
<td>25%</td>
<td>26%</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>37%</td>
<td>35%</td>
<td>39%</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
<td>46%</td>
<td>45%</td>
<td>47%</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>55%</td>
<td>54%</td>
<td>57%</td>
</tr>
<tr>
<td>5</td>
<td>0.9</td>
<td>64%</td>
<td>63%</td>
<td>66%</td>
</tr>
<tr>
<td>6</td>
<td>1.0</td>
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<td>75%</td>
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<tr>
<td>7</td>
<td>1.1</td>
<td>79%</td>
<td>79%</td>
<td>81%</td>
</tr>
<tr>
<td>8</td>
<td>1.2</td>
<td>85%</td>
<td>85%</td>
<td>86%</td>
</tr>
<tr>
<td>9</td>
<td>1.3</td>
<td>89%</td>
<td>90%</td>
<td>89%</td>
</tr>
<tr>
<td>10</td>
<td>1.4</td>
<td>93%</td>
<td>93%</td>
<td>92%</td>
</tr>
<tr>
<td>11</td>
<td>1.5</td>
<td>95%</td>
<td>95%</td>
<td>94%</td>
</tr>
<tr>
<td>12</td>
<td>1.6</td>
<td>97%</td>
<td>97%</td>
<td>96%</td>
</tr>
</tbody>
</table>

**Table 5.2**

Cobalt indicator thresholds and percentiles

<table>
<thead>
<tr>
<th>Indicator Bin</th>
<th>Threshold Co%</th>
<th>Grade Control</th>
<th>Actual Exploration</th>
<th>Alternative Exploration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.03</td>
<td>35%</td>
<td>36%</td>
<td>40%</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>53%</td>
<td>55%</td>
<td>53%</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
<td>65%</td>
<td>66%</td>
<td>65%</td>
</tr>
<tr>
<td>4</td>
<td>0.06</td>
<td>73%</td>
<td>74%</td>
<td>74%</td>
</tr>
<tr>
<td>5</td>
<td>0.07</td>
<td>78%</td>
<td>79%</td>
<td>79%</td>
</tr>
<tr>
<td>6</td>
<td>0.08</td>
<td>83%</td>
<td>83%</td>
<td>84%</td>
</tr>
<tr>
<td>7</td>
<td>0.09</td>
<td>86%</td>
<td>86%</td>
<td>87%</td>
</tr>
<tr>
<td>8</td>
<td>0.10</td>
<td>88%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>9</td>
<td>0.11</td>
<td>90%</td>
<td>91%</td>
<td>92%</td>
</tr>
<tr>
<td>10</td>
<td>0.12</td>
<td>92%</td>
<td>93%</td>
<td>93%</td>
</tr>
<tr>
<td>11</td>
<td>0.13</td>
<td>93%</td>
<td>94%</td>
<td>95%</td>
</tr>
<tr>
<td>12</td>
<td>0.14</td>
<td>94%</td>
<td>95%</td>
<td>96%</td>
</tr>
</tbody>
</table>
The flat-lying geometry and vertical geochemical zonation of the study area dictates that the vertical direction is the minor axis of anisotropy. Anisotropy in the horizontal plane was investigated through semivariogram maps computed using 50 metre square by two metre high cells for seven lags of the central slice of the variogram solid. The results were standardised to the data variance in all computations. Semivariogram maps were computed for the traditional semivariogram and the selected indicator thresholds for each element. The VARMAP outputs were then imported to MS Excel and displayed with a contouring chart tool. A colour palette was set to display results up to the level of the data variance in a colour scheme of 10% increments of the data variance. Above this notional sill level, higher 10% increments were shaded in a grey scale scheme.

The patterns in the semivariogram surface maps were inspected to interpret the major and intermediate axes of anisotropy. Directional semivariograms were then computed along the directions of the interpreted axes of anisotropy using the GAMV program. In some cases, a direction of greater continuity was not apparent, due to isotropic behaviour or poorly structured experimental semivariograms. In these instances, a likely direction of greater continuity was interpreted based on geological inference or adjacent threshold indicator results and the directional semivariograms were then computed as a final test for presence of anisotropy.

In the minor axis, vertical direction, the directional semivariogram was computed using two metre lags with a one-metre lag tolerance. In the horizontal plane, lag separations were set to 12.5 metres (6.25 m lag tolerance) to capture the short-range information. Bandwidths were set to 50 m in the horizontal plane and 10 m in the vertical direction to minimise the impact of the vertical zonation. The
variography summary plots in Appendix A and Appendix B include the semivariogram maps, directional semivariograms and tables summarising the models fitted to the experimental data. Like the semivariogram surface maps, all the computed semivariogram values were standardised to the data variance such that the plotted gamma value of one represents the data variance.

Results from the GAMV semivariogram computations were compiled into Excel spreadsheets and semivariogram models were fitted to the experimental data. In all cases, a combination of a nugget and nested spherical semivariogram models were used to model the continuity of the experimental results. The models were fitted under the assumption of geometric anisotropy with multiple nested structures fitted to the experimental data in each case.

5.2 Nickel variography

All nickel semivariogram maps for the in situ and the unfolded sample configurations of the actual exploration pattern, the alternative exploration pattern, and grade control pattern are compiled on summary plots in Appendix A.

5.2.1 Actual exploration pattern nickel traditional variography

Traditional semivariogram maps for in situ and unfolded nickel grades in the actual exploration pattern are shown in Figure 5.1.
The semivariogram maps reveal a 070° direction of greatest nickel grade continuity for both the in situ and unfolded cases. The direction interpreted is more pronounced in the unfolded case.

Traditional directional semivariograms for nickel grades along the axes of anisotropy of the in situ and unfolded cases are compared in Figure 5.2. The parameters of the models fitted to the experimental data points are listed in Table 5.3.
Several features are of interest including:

- The models interpreted for the minor axis (vertical) directional semivariograms are identical for both the in situ and unfolded cases, because the unfolding method does not affect the sample pair separation in the vertical direction.

- A nugget and three nested structures have been interpreted to fit the experimental data points. This number of structures was required for a good fit for the vertical semivariogram. Fewer structures could have been fitted in the horizontal plane however; the same numbers of structures were kept as part of a systematic approach to interpretation and parameter checking.

- Unfolding improves the structure of the horizontal plane semivariograms such that the short range continuity can be more confidently modelled.

5.2.2 Actual exploration pattern nickel indicator variography

The graphs in Figure 5.3 summarise the nugget, sill values, and major axis directions for models fitted to the indicator semivariograms of the in situ and unfolded
cases of the actual exploration pattern. Figure 5.4 summaries the indicator ranges for the structures modelled for the in situ and unfolded cases. The detailed variography is compiled on plots VAR.002 and VAR.003 in Appendix A.

Figure 5.3 Nickel indicator sills and major axis bearings, actual exploration pattern
Several features of the nickel indicator continuity of the actual exploration pattern are of interest:

- The indicator semivariogram maps for both the in situ and unfolded nickel cases show a pattern of decreasing range in the horizontal plane with increasing nickel grade thresholds.

- Isotropic behaviour in the horizontal plane has been interpreted above the 1.0% Ni cut off in both cases.

- The direction of greatest continuity trends east-west up to the 0.7% Ni indicator, then rotates to a more northeast-southwest trend.

- The interpreted indicator nugget values are relatively consistent but show marginally higher nuggets for grades exceeding 1.0% Ni.
• Both the in situ and unfolded cases have a pattern of decreasing continuity with increasing nickel grade. The interpreted continuity for the unfolded case is greater than the in situ case, particularly for thresholds below 1.0% Ni.

5.2.3 Alternative exploration pattern nickel traditional variography

Traditional semivariogram maps for in situ and unfolded nickel grades in the alternative exploration pattern are shown in Figure 5.5.

Figure 5.5 Nickel traditional semivariogram maps, alternative exploration pattern

A 070° trend of greater nickel continuity has been interpreted from in situ semivariogram map while the unfolded map has a more isotropic contour pattern. However, the directional semivariogram computed for 090°, as discussed below, does show some anisotropy over longer ranges.

Traditional directional semivariograms computed for nickel grades along the axes of anisotropy of the in situ and unfolded cases of the alternative exploration pattern are compared in Figure 5.6. The parameters of the models fitted are listed in Table 5.4.
Figure 5.6 Nickel traditional semivariograms, alternative exploration pattern

Table 5.4
Nickel traditional semivariogram parameters, alternative exploration pattern

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Sills</th>
<th>In situ Ranges</th>
<th>Unfolded Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minor</td>
<td>Semi major</td>
</tr>
<tr>
<td>Nugget</td>
<td>2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure 1</td>
<td>45%</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>Structure 2</td>
<td>30%</td>
<td>12</td>
<td>50</td>
</tr>
<tr>
<td>Structure 3</td>
<td>23%</td>
<td>15</td>
<td>100</td>
</tr>
</tbody>
</table>

Several features of the nickel continuity of the actual exploration pattern are of interest including:

- The vertical semivariograms are well structured and have been modelled with a nugget and three spherical structures that were applicable to the actual exploration pattern.

- In the horizontal plane, the in situ directional semivariograms are poorly structured. However, the structure is improved in the unfolded case.
5.2.4 Alternative exploration pattern nickel indicator variography

The graphs in Figure 5.7 summarise the nugget, sill values, and major axis directions interpreted for the models fitted to the in situ and unfolded indicator semivariograms of the alternative exploration pattern. The graphs in Figure 5.8 summarise the interpreted indicator ranges for the two cases.

![Figure 5.7 Nickel indicator sills and major axis bearings, alternative exploration pattern](image)

The detailed supporting variography is compiled on plots VAR.004 and VAR.005 in Appendix A.
Several features of nickel indicator continuity of the alternative exploration pattern are of interest:

- The semivariogram maps for both the in situ and unfolded cases show a pattern of decreasing nickel range with increasing cut off grade. However, the semivariogram value contours are noisier than the comparable maps from the actual exploration pattern.

- A pattern of rotational anisotropy is apparent in the in situ case but the particular direction of greater continuity is discernible in the unfolded semivariogram maps. A nominal direction of 090° was interpreted to test for possible anisotropy in directional semivariograms.
• The pattern of nugget values decreases with increasing cut off grade. This decreasing pattern is opposite to the indicator nugget behaviour of the actual exploration pattern, where nugget values decrease with increasing cut off.

• The minor axis (vertical) directions show a pattern of greater continuity for the middle thresholds and less continuity for the higher and lower cut off grades. This pattern of continuity is different to the actual exploration pattern where the pattern was one of consistent range to 1.3% Ni cut off then decreasing ranges for higher cut offs.

• In the horizontal plane, the general pattern of ranges is shorter than that interpreted from the actual exploration pattern. However, over the short range the alternative pattern experimental semivariograms display better structure than those computed from the actual exploration pattern.

• Unfolding of the alternative exploration pattern data results in longer interpreted ranges than the comparable semivariograms of the in situ results, particularly for the major axis direction.

5.2.5 Grade control pattern nickel traditional variography

An analysis of the nickel grade control continuity in the grade control sampling was carried out to determine the underlying pattern available to the exploration patterns. The traditional semivariogram map for the grade control pattern is shown in Figure 5.9.
The grade control semivariogram map reveals a pattern approximately northeast-southwest of longer continuity with an interpreted bearing of 050°. However, the map also shows a possible longer range southeast-northwest trend in higher value semivariogram contours. Traditional directional semivariograms computed for nickel grades along the interpreted axes of anisotropy of the grade control pattern are compared in Figure 5.10 and confirm a longer overall range for the north easterly direction. The parameters of the models fitted to the experimental data points are listed in Table 5.5.
All directional semivariograms are well structured, due to the higher data density in the grade control pattern. The interpreted model reveals the detailed pattern of nickel continuity for the study region is moderately anisotropic with a maximum range of 175 m along the major axis and 150 m along the semi major axis.

When the grade control model is compared to the exploration configuration models conclusions can be drawn as to the accuracy of the wider spaced exploration sampling; given that the grade control model is supported by well structured experimental semivariograms. Conclusions of interest are:

- The pattern of nickel continuity in the vertical direction is accurately captured by both exploration sampling configurations. The same combination of nugget and nested structures gives a good fit to the data from all patterns.
• The exploration patterns result in over estimation of the nickel grade continuity over the short to intermediate range. Despite local clusters of short spaced samples, the underlying short range continuity is not clear.

• The exploration patterns result in some degree of over or underestimation of the underlying detailed nickel continuity, suggesting additional close-spaced drilling is required at the exploration phase to correctly identify the semivariogram. However, the nugget is correctly determined at the exploration stage from the close-spaced vertical sampling.

5.2.6 Grade control pattern nickel indicator variography

The graphs in Figure 5.11 summarise the nugget, sill values, and major axis directions interpreted for the indicator semivariograms of the grade control pattern. The graphs in Figure 5.8 summarise the interpreted indicator ranges. The supporting variography is compiled on plot VAR.001 in Appendix A.

![Figure 5.11 Nickel indicator sills and major axis bearing, grade control pattern](image-url)
Features of interest of the grade control indicator variography include:

- The semivariograms show a pattern of decreasing range with increasing nickel threshold, and a pattern of rotating anisotropy with increasing cut-off.

- The indicator sills are relatively consistent being 20 to 25% of the data variance. The vertical ranges are also consistent up to the 1.3% Ni threshold, then decreasing in range rapidly with increasing cut-off grade.

- The horizontal plane indicator ranges are long for the lower thresholds but decrease markedly at the 0.8% Ni threshold. Above this cut off the pattern of nickel continuity is more isotropic.

- Inspection and comparison of the grade control indicator results, to the exploration sampling nickel indicator variography reveals that the underlying trends of continuity are generally captured by all the exploration sampling configurations, albeit with lower accuracy.
5.3 Cobalt variography

All cobalt variography is presented in the same manner as the nickel results with summary plots for in situ and unfolded sampling configurations compiled in Appendix B.

5.3.1 Actual exploration pattern cobalt traditional variography

Traditional semivariogram maps for in situ and unfolded cobalt grades in the actual exploration pattern are shown in Figure 5.13.

![Figure 5.13 Cobalt traditional semivariogram maps, actual exploration pattern](image)

The traditional semivariogram maps for the in situ pattern indicates a 100° trend of greatest cobalt grade continuity. The map for the unfolded data shows a similar interpreted direction (110°).

Traditional directional semivariograms, computed for cobalt grades along the axes of anisotropy for the in situ and unfolded cases of the actual exploration pattern, are compared in Figure 5.14. The parameters of the models fitted are listed in Table 5.6.
Figure 5.14 Cobalt traditional semivariograms, actual exploration pattern

Table 5.6
Cobalt traditional semivariogram parameters, actual exploration pattern

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Sills</th>
<th>In situ Range (m)</th>
<th>Unfolded Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minor</td>
<td>Semi major</td>
</tr>
<tr>
<td>Nugget</td>
<td>25%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure 1</td>
<td>40%</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>Structure 2</td>
<td>25%</td>
<td>8</td>
<td>50</td>
</tr>
<tr>
<td>Structure 3</td>
<td>10%</td>
<td>10</td>
<td>150</td>
</tr>
</tbody>
</table>

Features of interest in the actual exploration cobalt variography include:

- The vertical minor axis semivariograms are well structured with a range of 10 m. This range is 5 m shorter than for the corresponding nickel vertical semivariogram (Table 5.5).
- A nugget equivalent to 25% of the data variance was fitted with three structures interpreted to fit the experimental data points.
• The horizontal plane semivariograms are poorly structured, particularly for the unfolded case. This poor structure is the reason why an isotropic model was fitted to the unfolded directional semivariogram.

• Unlike the corresponding nickel examples, where unfolding improved the horizontal plane semivariogram structure, unfolding of the cobalt data produced no improvement. This lack of improvement reflects the geologically less continuous nature of cobalt as noted in Figure 4.4.

5.3.2 Actual exploration pattern cobalt indicator variography

The graphs in Figure 5.15 summarises the nugget, sill values, and major axis directions for the models fitted to the indicator semivariograms of the in situ and unfolded cases of the actual exploration pattern. Figure 5.16 summaries the indicator ranges for the structures modelled for the in situ and unfolded cases.

The graphs in Figure 5.15 summarise the nuggets, sill values, and indicator semivariogram ranges for the models fitted to the in situ and unfolded indicator semivariograms of cobalt in the actual exploration pattern. Supporting variography is compiled on plots VAR.007 and VAR.008 in Appendix B.
Figure 5.15 Cobalt indicator sills and major axis bearings, actual exploration pattern

Figure 5.16 Cobalt indicator semivariogram ranges, actual exploration pattern
Key features of the patterns of cobalt indicator continuity include:

- The contours of the indicator semivariogram maps of the unfolded case (Appendix B) suggest greater continuity than for the in situ case.

- At lower thresholds, there is a southwesterly trend of greater continuity. This direction cross cuts the trends noted in the nickel indicator variography suggesting a possibly different geological control for the cobalt mineralisation.

- The cobalt indicator nuggets that are consistent for in situ configuration, are in contrast to the pattern of increasing nuggets with higher thresholds in the unfolded case.

- The vertical (minor axis) ranges are similar for the in situ and unfolded cases.

- The in situ configuration has a pattern of increasing ranges for higher thresholds, while the unfolded pattern suggests ranges decrease for higher cut off grades.

5.3.3 Alternative exploration pattern cobalt traditional variography

Traditional semivariogram maps for in situ and unfolded cobalt grades in the alternative exploration pattern are shown in Figure 5.17.
The contours in both semivariogram maps are poorly structured and have no preferred direction of cobalt grade continuity in the horizontal plane. However, an additional test for anisotropy was made by computing directional semivariograms along the grid directions.

Traditional directional semivariograms, computed for cobalt grades along the grid axes of the in situ and unfolded cases of the alternative exploration pattern, are compared in Figure 5.18. Table 5.7 lists the parameters of the models fitted to the directional semivariograms.
Table 5.7

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Sills</th>
<th>In situ Range (m)</th>
<th>Unfolded Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minor</td>
<td>Major</td>
</tr>
<tr>
<td>Nugget</td>
<td>20%</td>
<td>Minor</td>
<td>Major</td>
</tr>
<tr>
<td>Structure 1</td>
<td>35%</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Structure 2</td>
<td>25%</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>Structure 3</td>
<td>20%</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

Features of interest in the cobalt variography of the alternative exploration include:

- The vertical semivariograms are well structured, with similar ranges to the actual exploration pattern results (Figure 5.6). However, the nugget value is 5% lower than the corresponding semivariogram in the actual exploration pattern.

- An isotropic model has been fitted to the in situ case in the horizontal plane.
• The horizontal plane 180° direction is poorly structured for both cases but the 90° directions have reasonable structure. The structure in this direction is significantly better than the structure of the semivariograms in the actual exploration pattern (Figure 5.14).

• Similar to the actual exploration pattern result, unfolding does not improve the experimental semivariogram structure of cobalt.

5.3.4 Alternative exploration pattern cobalt indicator variography

The graphs in Figure 5.19 summarises the nugget, sill values, and major axis directions for models fitted to the indicator semivariograms of the in situ and unfolded cases of the actual exploration pattern. Figure 5.20 summaries the indicator ranges for the structures modelled for the in situ and unfolded cases. Supporting variography is compiled on plots VAR.009 and VAR.010 in Appendix B.

<table>
<thead>
<tr>
<th>Indicator Sills</th>
<th>Major Axis Bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In situ</strong></td>
<td><strong>Unfolded</strong></td>
</tr>
<tr>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 5.19 Cobalt indicator sills and major axis bearings, alternative exploration pattern
Figure 5.20 Cobalt indicator semivariogram ranges, alternative exploration pattern

Features of interest in the cobalt indicator variography of the alternative exploration pattern include:

- The semivariogram maps of both the in situ and unfolded cases (Appendix B) are noisier than the comparable maps from the actual exploration pattern. The maps only show discernible structure for the lowest three thresholds.

- The vertical indicator semivariograms are well structured and similar indicator models can be fitted to the minor axis semivariograms of the in situ and unfolded cases. Both cases display a pattern of increasing nugget and decreasing range with increasing indicator threshold.
The pattern of decreasing range with increasing cut off also applies in the horizontal plane, however, the ranges fitted to the unfolded case are longer than those fitted to the in situ case.

5.3.5 Grade control pattern cobalt traditional variography

Similar to the nickel analysis, the grade control variography was investigated to determine the effectiveness of the two exploration patterns. The traditional semivariogram map is shown in Figure 5.21.

![Figure 5.21 Cobalt traditional semivariogram map, grade control pattern](image)

The contours of the traditional semivariogram map reveal a 100° trend of maximum continuity. Traditional directional semivariograms, computed for cobalt grades along the axes of anisotropy of the grade control pattern, are compared in Figure 5.22. The parameters of the model fitted to the experimental data points are listed in Table 5.8.
Features of interest in the grade control cobalt semivariograms include:

- The nugget of the grade control data is substantially lower than that interpreted from the exploration sampling configurations.

- The major axis maximum range is four times longer than the intermediate axis, however, 55% of the data variance is accommodated within an isotropic 10 m range.

- Comparing the grade control results to the exploration pattern models shows that there is a tendency to overstate the short range continuity in the horizontal plane for both patterns and for both the in situ and unfolded cases. For the longer-range structures, the in situ case is more comparable to the grade control results for the actual exploration pattern and the unfolded case is more accurate for the alternative exploration pattern.
5.3.6 Grade control cobalt indicator variography

The graphs in Figure 5.23 summarise the nugget, sill values, and major axis directions for models fitted to the indicator semivariograms of the grade control pattern. Figure 5.24 summarises the indicator ranges for the structures modelled for the in situ and unfolded cases. Supporting variography is compiled on plot VAR.006 in Appendix B.

Figure 5.23 Cobalt indicator sills and major axis bearings, grade control pattern

Figure 5.24: Cobalt indicator semivariogram ranges, grade control pattern
Features of the grade control indicator cobalt continuity include:

- The indicator semivariogram maps show a pattern of short range continuity with a general east west trend of longest continuity.

- The nugget values are consistently 20 to 25% of the sill for all thresholds.

- The indicator ranges show a pattern of decreasing range with increasing cobalt threshold.

- The grade control pattern of decreasing range with increasing threshold is a smoother transition than interpreted from the exploration patterns.
6 Estimation

Both ordinary point kriging and multiple indicator point kriging algorithms were used to estimate the locations of the in situ grade control sample locations. The jackknife option of the GSLIB programs KT3D and IK3D was used for the estimation of these point locations. The parameter files for these programs for each estimate completed in this thesis are compiled in Appendix C of this report.

Jackknife is a cross-validation type method, whereby the estimates are computed at locations listed in a jackknife file. KT3D and IK3D report the estimate and the true value at that location from the input data. For the estimation of nickel and cobalt described below, the jackknife file comprised the grade control data locations and the data input files comprised the actual exploration and alternative exploration sampling configurations. One disadvantage of the jackknife process is that if the jackknife file and the data file both contain a data point at the same location, the program considers that the data information does not exist. The program therefore makes an estimate at the data location from the nearest available samples as per standard cross-validation. To overcome this issue, where estimates were made at data locations coincident with the input file; the original data value was substituted. This approach is consistent with point kriging at the data location that results in the estimated value being the data value.

Sample selection parameters set for estimation included a minimum of four and a maximum of 16 samples for each estimate and an octant search method that required at least four samples per octant. This approach was used to capture a representative number of samples for the local area while minimising the effect of
inappropriate kriging weights at the ends of sample strings as depicted in Figure 3.3.

Indicator estimation thresholds were set to the same as those used for the variography (Table 5.1 and Table 5.2) and an E-type estimate was computed from the output indicator kriging distributions using the GSLIB PostIK program. A power model lower tail (omega = 1.5) and hyperbolic model upper tail (omega = 1.5) functions were used for extrapolation above and below the minimum and maximum thresholds. Linear interpolation was used between indicator thresholds. These models were considered reasonable in light of the histogram shapes (Figure 4.8) and the recommended values by Deutsch and Journel [1998] for metal distributions.

6.1 Nickel estimates

Nickel estimates were computed for the grade control locations for the eight combinations of sampling configurations (actual and alternative pattern), estimation method, and in situ and unfolded cases.

6.1.1 Nickel estimate indicator kriging order relation corrections

The indicator kriging estimates required the order relation corrections (section 2.7) that are listed in Table 6.1.
Table 6.1
Order relations corrections for indicator kriging nickel estimates

| Threshold | Actual Exploration | | | Alternative Exploration | | |
|---|---|---|---|---|---|
|  | In situ | Unfolded | In situ | Unfolded |
| # | %Ni | Number | Average | Number | Average | Number | Average |
| 1 | 0.5 | 8 | 0.0100 | 9 | 0.0056 | 86 | 0.0086 |
| 2 | 0.6 | 8 | 0.0083 | 39 | 0.0017 | 134 | 0.006 |
| 3 | 0.7 | 10 | 0.0047 | 44 | 0.0011 | 144 | 0.007 |
| 4 | 0.8 | 24 | 0.0029 | 59 | 0.0006 | 156 | 0.007 |
| 5 | 0.9 | 53 | 0.0016 | 151 | 0.0004 | 178 | 0.0054 |
| 6 | 1 | 123 | 0.0007 | 276 | 0.0002 | 243 | 0.0038 |
| 7 | 1.1 | 196 | 0.0004 | 384 | 0.0001 | 315 | 0.0027 |
| 8 | 1.2 | 404 | 0.0002 | 560 | 0.0001 | 477 | 0.0014 |
| 9 | 1.3 | 755 | 0.0001 | 811 | 0.0001 | 719 | 0.0005 |
| 10 | 1.4 | 921 | 0.0001 | 1008 | 0.0001 | 848 | 0.0004 |
| 11 | 1.5 | 1167 | 0.0000 | 1230 | 0.0000 | 924 | 0.0004 |
| 12 | 1.6 | 1324 | 0.0000 | 1376 | 0.0000 | 1105 | 0.0002 |
| Total / Average | 4993 | 0.0002 | 5947 | 0.0001 | 5329 | 0.0016 |

The number and magnitude of order relation corrections was higher for the alternative exploration patterns. For the same pattern, there are more corrections for the unfolded case but the magnitude is similar to that of the in situ results. Overall, the magnitude of corrections was small in relation to the average nickel grades. Subsequent analyses and validation results discussed later in the chapter show that the corrections have not adversely affected the indicator kriging estimates.

6.1.2 Summary statistics of nickel estimates

Summary statistics for the 13,414 nickel estimates derived from the actual and alternative exploration sampling configurations for the four estimation methods are listed in Table 6.2. The summary statistics from the grade control pattern are also included for reference.
Table 6.2
Nickel estimates summary statistics

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Grade Control Data</th>
<th>Actual exploration pattern</th>
<th>Alternative exploration pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In situ</td>
<td>Unfolded</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OK</td>
<td>IK</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.07</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.67</td>
<td>2.23</td>
<td>2.23</td>
</tr>
<tr>
<td>Range</td>
<td>2.61</td>
<td>2.09</td>
<td>2.09</td>
</tr>
<tr>
<td>Mean</td>
<td>0.85</td>
<td>0.85</td>
<td>0.87</td>
</tr>
<tr>
<td>Median</td>
<td>0.81</td>
<td>0.83</td>
<td>0.84</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.38</td>
<td>0.23</td>
<td>0.24</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>0.44</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.49</td>
<td>0.74</td>
<td>0.83</td>
</tr>
</tbody>
</table>

The mean grades of the all estimates are very similar albeit that the indicator kriging means are marginally higher than the ordinary kriging means. The unfolded estimates have higher dispersion than the ordinary kriging estimates. When compared to the grade control ‘reality’ statistics, all estimates have close reproduction of the mean and median but the dispersion as quantified by the standard deviation is much lower.

6.1.3 Estimation error nickel estimates

Table 6.3 summarises the error statistics for all nickel estimates relative to the actual values of the grade control data.
Table 6.3
Nickel estimation error statistics

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Actual exploration pattern</th>
<th>Alternative exploration pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In situ</td>
<td>Unfolded</td>
</tr>
<tr>
<td></td>
<td>OK</td>
<td>IK</td>
</tr>
<tr>
<td>Minimum</td>
<td>-1.290</td>
<td>-1.328</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.99</td>
<td>1.95</td>
</tr>
<tr>
<td>Range</td>
<td>3.28</td>
<td>3.28</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.003</td>
<td>-0.022</td>
</tr>
<tr>
<td>Median</td>
<td>0.000</td>
<td>-0.005</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.33</td>
<td>0.34</td>
</tr>
<tr>
<td>Mean absolute error</td>
<td>0.25</td>
<td>0.26</td>
</tr>
</tbody>
</table>

All estimates have average errors very close to zero and very similar mean absolute error (MAE) values. The MAE values for the actual exploration pattern are marginally lower than the corresponding alternative exploration pattern results.

The nickel estimate distributions of both sampling configurations are compared in the Q-Q plots of Figure 6.1.
The Q-Q plots confirm the presence of conditional bias in the estimates, whereby the reality grade control values are overestimated below the grade control median (0.8% Ni) and underestimated above the median for all estimates. The extreme values, above the 99th percentile are the most underestimated. Both unfolding and indicator kriging estimation reduce the degree of bias above the grade control median, which is important in terms of high grade estimation. The unfolded,
indicator kriging estimate has the best correspondence with the grade control data distribution for both the actual and alternative exploration pattern.

**6.1.4 Example nickel estimates cross sections**

Figure 6.2 compares profiles of nickel grades for the input grade control data with actual exploration pattern nickel estimates at section 200 metres north (mN). This section was selected because it occurs in the middle of the study area. The section is presented looking north with a vertical exaggeration of 2:1. The locations of drill hole paths for the actual exploration pattern are shown as vertical black lines.

The grade control section in Figure 6.2 reveals two lensoidal cores of high grade (>1.25 %) nickel mineralisation with the larger zone of high grade on the eastern (right hand) side of the study region. The high grade cores are disconnectedly
joined by lower grade (1.0 to 1.25 % Ni) material. The estimate sections reproduce the grade control data pattern of nickel grade distribution but with more definite connection of the high grade cores by the lower grade material. The unfolded estimate section shows a very similar pattern of nickel grade distribution to the in situ estimate with only marginally more very high grade (>1.5 % Ni) mineralisation apparent. Importantly, the unfolding results in the estimation of sporadic high grades through the zone of connection between the two high grade cores as indicated by the grade control data. The indicator kriging section is comparable to the unfolded ordinary kriging section in terms of grade distribution and the amount of high grade mineralisation but lacks the sporadic high grades through the central connection zone. The unfolded indicator kriging section shows the highest proportion of very high grade mineralisation and best reproduces the pattern seen in the grade control section, albeit in a smoother manner.

Figure 6.3 compares the alternative exploration pattern estimates to grade control, also for the same cross sections as the actual exploration results (200 mN). Drill hole locations for the alternative exploration pattern on this section are shown as vertical black lines.
The two cores of high grade mineralisation discussed for the actual exploration sections are also apparent in the estimation sections of the alternative exploration pattern. However, compared with the profiles in Figure 6.2, the extent of the eastern high grade cores is larger and the western core is smaller. In all other aspects, the comments applied to the actual exploration sections are applicable to the estimation sections of the alternative pattern.

6.1.5 Nickel grade-volume estimates

In terms of mine planning, the corrected estimation of the volume of high grade material is critical in the early years of deposit exploitation. Despite the fact that the estimation results and input data are point values, pseudo grade-volume curves have been generated for each estimate by assuming that each node represents an
ore block of dimension 12.5 mE by 12.5 mN by 2 mRL (metres reduced level).

Figure 6.4 shows these curves for the actual exploration pattern (left) and the alternative exploration pattern (right). The results have been plotted using a log x-scale to highlight the volume differences of high grade material. The in situ and unfolded estimates are shown as well as the curve generated from the grade control data points at which the other estimates were made.

The grade-volume results show that all estimates understate the volume of high grade (>1% Ni) material with respect to the grade control volume, with the degree of underestimation increasing with increasing grade. This effect is expected from kriging methods as the local neighbourhood estimate will always be of lower grade than the highest grade sample in the local area. For both sampling configurations, the ordinary kriging method results in the poorest reproduction of the underlying grade volume relationship. The unfolded ordinary kriging method only gives a marginal improvement over in situ ordinary kriging estimation. The indicator kriging method gives an improvement of the estimate of high grade
material and unfolding improves the estimate further. The combination of unfolding and indicator kriging estimation results in a grade-volume curve that is closest to the grade control results. Table 6.4 below highlights the differences between the estimates and grade control for a 1.2% Ni cut off grade.

Table 6.4  
Nickel estimate grade-volume for 1.2% Ni cut off grade

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Grade Control</th>
<th>Actual exploration pattern</th>
<th>Alternative exploration pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In situ</td>
<td>Unfolded</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OK</td>
<td>IK</td>
</tr>
<tr>
<td>Nodes</td>
<td>3307</td>
<td>1703</td>
<td>1914</td>
</tr>
<tr>
<td>Grade</td>
<td>1.36</td>
<td>1.28</td>
<td>1.31</td>
</tr>
<tr>
<td>Metal</td>
<td>4490</td>
<td>2180</td>
<td>2501</td>
</tr>
<tr>
<td>Grade</td>
<td>100%</td>
<td>51%</td>
<td>58%</td>
</tr>
<tr>
<td>Metal</td>
<td>100%</td>
<td>94%</td>
<td>96%</td>
</tr>
<tr>
<td>Grade</td>
<td>100%</td>
<td>49%</td>
<td>56%</td>
</tr>
</tbody>
</table>

Table 6.4 shows that all estimation methods return grade estimates of the high grade within a few percent of the grade control value. However, the volume of high grade is clearly understated for all estimated methods when compared to the high grade defined by the grade control sampling.

The differences between the estimates of high grade between the actual and alternative exploration pattern are minor. For a given estimation method, the total volume and grade are similar. Additionally, the estimates of volume and of high grade by the alternative exploration pattern are as good or marginally better than the actual exploration pattern estimates.
6.2 **Cobalt estimates**

Cobalt estimates were computed for the grade control locations for the six combinations of sampling configurations (actual and alternative pattern), estimation methods, and in situ and unfolded cases.

6.2.1 **Cobalt estimate indicator kriging order relation corrections**

The cobalt indicator kriging estimates required the order relation corrections that are listed in Figure 6.3.

<table>
<thead>
<tr>
<th>Threshold</th>
<th>% Ni</th>
<th>Number</th>
<th>Average</th>
<th>Number</th>
<th>Average</th>
<th>Number</th>
<th>Average</th>
<th>Number</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Actual Exploration</td>
<td>Alternative Exploration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>In situ</td>
<td>Unfolded</td>
<td>In situ</td>
<td>Unfolded</td>
<td>In situ</td>
<td>Unfolded</td>
<td>In situ</td>
<td>Unfolded</td>
</tr>
<tr>
<td>#</td>
<td>% Ni</td>
<td>Number</td>
<td>Average</td>
<td>Number</td>
<td>Average</td>
<td>Number</td>
<td>Average</td>
<td>Number</td>
<td>Average</td>
</tr>
<tr>
<td>1</td>
<td>0.03</td>
<td>10</td>
<td>0.0047</td>
<td>9</td>
<td>0.0033</td>
<td>45</td>
<td>0.005</td>
<td>127</td>
<td>0.0068</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>24</td>
<td>0.0027</td>
<td>43</td>
<td>0.0014</td>
<td>78</td>
<td>0.0042</td>
<td>212</td>
<td>0.0062</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
<td>68</td>
<td>0.0017</td>
<td>92</td>
<td>0.0010</td>
<td>103</td>
<td>0.003</td>
<td>273</td>
<td>0.0051</td>
</tr>
<tr>
<td>4</td>
<td>0.06</td>
<td>111</td>
<td>0.0014</td>
<td>120</td>
<td>0.0004</td>
<td>142</td>
<td>0.003</td>
<td>346</td>
<td>0.0037</td>
</tr>
<tr>
<td>5</td>
<td>0.07</td>
<td>173</td>
<td>0.0009</td>
<td>190</td>
<td>0.0003</td>
<td>222</td>
<td>0.0017</td>
<td>442</td>
<td>0.0031</td>
</tr>
<tr>
<td>6</td>
<td>0.08</td>
<td>210</td>
<td>0.0007</td>
<td>239</td>
<td>0.0003</td>
<td>289</td>
<td>0.0012</td>
<td>545</td>
<td>0.0026</td>
</tr>
<tr>
<td>7</td>
<td>0.09</td>
<td>307</td>
<td>0.0005</td>
<td>337</td>
<td>0.0001</td>
<td>340</td>
<td>0.0009</td>
<td>611</td>
<td>0.0023</td>
</tr>
<tr>
<td>8</td>
<td>0.10</td>
<td>393</td>
<td>0.0003</td>
<td>404</td>
<td>0.0001</td>
<td>480</td>
<td>0.0006</td>
<td>732</td>
<td>0.0018</td>
</tr>
<tr>
<td>9</td>
<td>0.11</td>
<td>519</td>
<td>0.0002</td>
<td>490</td>
<td>0.0001</td>
<td>568</td>
<td>0.0005</td>
<td>809</td>
<td>0.0015</td>
</tr>
<tr>
<td>10</td>
<td>0.12</td>
<td>609</td>
<td>0.0002</td>
<td>555</td>
<td>0.0001</td>
<td>641</td>
<td>0.0004</td>
<td>910</td>
<td>0.0013</td>
</tr>
<tr>
<td>11</td>
<td>0.13</td>
<td>728</td>
<td>0.0001</td>
<td>664</td>
<td>0.0001</td>
<td>803</td>
<td>0.0002</td>
<td>1008</td>
<td>0.0010</td>
</tr>
<tr>
<td>12</td>
<td>0.14</td>
<td>878</td>
<td>0.0001</td>
<td>798</td>
<td>0.0001</td>
<td>943</td>
<td>0.0001</td>
<td>1103</td>
<td>0.0008</td>
</tr>
<tr>
<td>Total/Average</td>
<td>4030</td>
<td>0.0003</td>
<td>3941</td>
<td>0.0002</td>
<td>4654</td>
<td>0.0007</td>
<td>7118</td>
<td>0.0021</td>
<td></td>
</tr>
</tbody>
</table>

The number of order relation corrections for the cobalt indicator kriging estimates was similar to the number of corrections for the nickel indicator kriging estimates. The highest number of corrections was required for the alternative exploration pattern. However, the average magnitude of corrections was small and was not
considered to adversely affect the indicator kriging estimates based on the error analysis and validation results discussed later in this chapter.

6.2.2 Summary statistics of cobalt estimates

Summary statistics for the 13,411 cobalt estimates derived from the actual and alternative exploration sampling configurations for the four estimation methods are listed in Table 6.5.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Grade Control Data</th>
<th>Actual exploration pattern</th>
<th>Alternative exploration pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In situ</td>
<td>Unfolded</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.887</td>
<td>0.887</td>
<td>0.887</td>
</tr>
<tr>
<td>Range</td>
<td>0.886</td>
<td>0.886</td>
<td>0.886</td>
</tr>
<tr>
<td>Mean</td>
<td>0.058</td>
<td>0.055</td>
<td>0.060</td>
</tr>
<tr>
<td>Median</td>
<td>0.040</td>
<td>0.052</td>
<td>0.055</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.054</td>
<td>0.025</td>
<td>0.027</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>0.944</td>
<td>0.452</td>
<td>0.459</td>
</tr>
<tr>
<td>Skewness</td>
<td>3.560</td>
<td>4.987</td>
<td>3.746</td>
</tr>
</tbody>
</table>

The summary statistics for all cobalt estimates are similar, with mean grades ranging from 0.55% Co (OK in situ) to 0.61% Co (IK unfolded). These values are all close to that of the grade control data with the indicator kriging unfolded result returning the mean closest to the grade control value for both patterns. The median values, however, all overstate the underlying grade control median reflecting smoothing in the estimation methods. The dispersion of estimates as measured by the standard deviation is also similar but indicator kriging and unfolding results in marginally higher standard deviation and skewness values.
6.2.3 *Estimation error cobalt estimates*

Table 6.7 summarises the error statistics for all cobalt estimates relative to the actual values of the grade control data.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Actual exploration pattern</th>
<th>Alternative exploration pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In situ</td>
<td>Unfolded</td>
</tr>
<tr>
<td>Minimum</td>
<td>-0.204</td>
<td>-0.741</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.726</td>
<td>0.167</td>
</tr>
<tr>
<td>Range</td>
<td>0.930</td>
<td>0.908</td>
</tr>
<tr>
<td>Mean</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Median</td>
<td>-0.006</td>
<td>0.009</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.052</td>
<td>0.053</td>
</tr>
<tr>
<td>Mean absolute error</td>
<td>0.031</td>
<td>0.034</td>
</tr>
</tbody>
</table>

Table 6.7 shows that all estimates have average errors very close to zero and very similar mean absolute error (MAE) values. The ordinary kriging estimates for both patterns have the lowest errors, however, the error statistics for all estimate methods are very similar.

In Figure 6.5, Q-Q plots compare the cobalt estimate distributions of both sampling configurations to the grade control distribution. The plots have been generated using a log scale for both axes to highlight the differences between estimates.
The cobalt Q-Q plots reveal all estimates have a conditional bias with the bias pivoted near the upper quartile with respect to the X=Y line. Similar to the nickel results, unfolding and indicator kriging estimation reduces the degree of bias with the combination of both resulting in the least bias. However, the differences between the different estimates and exploration sampling patterns are marginal.
6.2.4 Example cobalt estimates cross sections

Figure 6.6 compares the profiles of cobalt grades for the input grade control data and the cobalt estimates of the actual exploration pattern looking north through the centre of the study area. The same cross section, 200 mN, is presented in each profile and the vertical exaggeration is 2:1.

The grade control section reveals multiple isolated pods of high grade (>0.08 % Co) cobalt mineralisation discontinuously joined by lower grade mineralisation (>0.04 % Co) across the section. The general undulation of the low grade connection zones is similar in shape to that of the low grade nickel spatial distribution in Figure 6.2. The pattern of high grade cobalt pods within a low grade envelope is reproduced in the estimation profiles but with minor variation in the volume of...
higher grade mineralisation. In all cases, the continuity of the high grade is greater than that seen in the grade control data.

Figure 6.7 compares the grade control profile of cobalt grades at section 200 mN to the same sections of the alternative exploration pattern estimates.

The patterns within the alternative exploration estimate sections are similar to those derived from the actual exploration pattern. High grade pods of cobalt occur within a lower grade envelope. The main feature different from the actual exploration results is the better definition in shape of the high grade pods within the local sampling clusters. However, away from the clusters there appears to be more smoothing of the high grade pods when compared to the results in Figure 6.6.
6.2.5 *Cobalt grade - volume estimates*

Figure 6.4 shows grade volume curves for the actual exploration pattern (left) and the alternative exploration pattern (right) for cobalt estimates. These have been constructed under the same assumptions as the nickel data with a log x-scale.

The results show that, similar to the nickel results described in section 6.1.5, all estimates understate the volume of high grade (>0.1% Co) material, with the degree of underestimation increasing with increasing grade. However, differences between the estimation methods are marginal. The combination of unfolding and indicator kriging results in a grade-volume curve that is closest to the grade control results but this is really only apparent below the 0.2 % Co threshold. Table 6.4 below highlights the differences between the estimates and grade control values for a 0.1% Co cut off grade.
Table 6.8
Cobalt estimate grade-volume for 0.1% Co cut off grade

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Grade Control</th>
<th>Grade</th>
<th>Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>OK 2126, IK 823</td>
<td>100% 314</td>
<td>100% 123</td>
</tr>
<tr>
<td>Grade</td>
<td>OK 0.148, IK 0.116</td>
<td>79% 96</td>
<td>79% 31</td>
</tr>
<tr>
<td>Metal</td>
<td>OK 314, IK 178</td>
<td>7% 57</td>
<td>7% 31</td>
</tr>
</tbody>
</table>

- **Actual exploration pattern**
  - In situ: OK 2126, IK 823
  - Unfolded: OK 1076, IK 2056

- **Alternative exploration pattern**
  - In situ: OK 397, IK 920
  - Unfolded: OK 671, IK 1419

Table 6.4 reveals that all estimation methods result in a similar degree of underestimation of the grade of the high grade cobalt material with all methods reporting in the range of 74% to 79% of the grade control cobalt value. The volume of material for this cut off is also underestimated in all cases, but the combination of unfolding and indicator kriging estimation returns the estimate closest to the grade control benchmark.

Comparing the high grade cobalt results to the high grade nickel results in Table 6.4 shows that the estimation improvement of indicator kriging and unfolding is less successful for cobalt estimation than for nickel. This result is interpreted to reflect the less continuous nature of cobalt high grade as noted in the cross sectional comparisons in Figure 6.6 and Figure 6.7.
7 CONCLUSIONS

With respect the hypotheses and conjectures presented on page 58, the following conclusions are drawn.

7.1 Grade connectivity

Unfolding by vertical translation improves the connectivity of the high grade values for both nickel and cobalt, as would be expected by the geological understanding of nickel laterite deposit formation. The increase in connectivity is greater for nickel than cobalt because nickel has greater continuity as demonstrated in the variography. Additionally, the unfolding surface defined to improve the connectivity during estimation is biased towards nickel grades due to the higher average concentration of nickel in the study region.

The improvements in grade connectivity are partly quantified by the improved traditional and indicator semivariogram structure of unfolded cases of the sampling configurations for nickel. However, unfolding did not improve the traditional semivariograms of cobalt, but the unfolded indicator cobalt semivariograms showed some improvement in short range structure when compared to the in situ cases of the two test sampling configurations.

The greatest impact on connectivity is in the estimation and this is apparent in the cross sections of nickel estimates (Figure 6.2 and Figure 6.3) and cobalt estimates (Figure 6.6 and Figure 6.7). For both ordinary kriging and indicator kriging estimates, and for both sampling configurations tested, the high grade values (>1.0%
Ni and >0.10% Co) have higher lateral connectivity in the unfolded cases than in the in situ cases.

However, it is important to note that despite the improvement in definition of high grade ore the combination of unfolding and indicator kriging estimation achieved, the volume of high grade in this best estimate was still well short of the volume indicated by the grade control information. This shortfall will always occur due to the smoothing effect of estimation.

### 7.2 Stratified sampling versus standard sampling configuration

The results from the stratified sampling approach (alternative exploration pattern) of several local clusters, compared to the standard approach (actual exploration pattern) of a regular grid and a local sampling clusters show that the alternative pattern does not improve the definition of the short range continuity. However, the variography reveals that the alternative pattern results in models of grade continuity that are as good as the actual exploration pattern. The estimation results show that the alternative exploration pattern results in estimates very similar to those from the actual exploration pattern. The important result here is that adopting the alternative pattern achieves a 20% cost saving without any major increase in the estimation error (Table 6.3 and Table 6.7) or difference in the definition of high grade material (Table 6.4 and Table 6.8).

### 7.3 Indicator kriging versus ordinary kriging

The comparison of estimation results from indicator kriging and ordinary kriging clearly shows that indicator kriging gives a better definition of the amount of higher grade nickel and cobalt mineralisation. The improvement, however, is
greatest for nickel. The cross sections (Figure 6.2, Figure 6.3, Figure 6.6 and Figure 6.7), Q-Q validation plots (Figure 6.1 and Figure 6.5), and grade volume curves (Figure 6.4 and Figure 6.8) all confirm better representation of the underlying grade control sampling when indicator estimation is applied.

7.4 Unfolded estimation

Grade estimation in unfolded space better predicts the grade-volume relationships as quantified by validation against comprehensive grade control sampling. This is also confirmed by the cross sections, Q-Q plots and grade volume curves for both nickel and cobalt. However, there is greater improvement in the estimation of high grade nickel mineralisation than for cobalt.

7.5 Recommendations

The primary conclusion and recommendation of this study is that the combination of indicator estimation and unfolding clearly improves the definition of the grade and quantity of high grade mineralisation that will be targeted in the early years of mining in a nickel laterite deposit of the style investigated (Murphy et.al., 2002). This result indicates that project viability can be enhanced at the exploration stage by adopting this approach towards resource estimation.

As a secondary recommendation, the estimation results derived from a stratified sampling pattern are comparable to those of the standard exploration approach and offer a major cost saving at the exploration stage of project evaluation.
8 References


Chilès, J.P, Bourgine, B., & Niandou, I. (1994). *Designing an additional sampling pattern to determine the variogram at short distances*. In: Proceed-


Appendix A

Nickel variography summary plots
Appendix B
Cobalt variography summary plots
Appendix C
GSLIB KT3D and IK3D parameter files
Parameters for KT3D - Actual Exploration Pattern OK Ni Estimate

START OF PARAMETERS:
G2Ni.dat                     -file with data
  1 2 3 5 0                  - columns for X, Y, Z, var, sec var
  -1.0e21 1.0e21             - trimming limits
  2                          -option: 0=grid, 1=cross, 2=jackknife
G1Ni.dat                     -file with jackknife data
  1 2 3 5 0                  - columns for X,Y,Z, vr and sec var
  1                          -debugging level: 0,1,2,3
G2Ni_kt3d.dbg                -file for kriged output
G2Ni_kt3d.dat                -file for debugging output
  50 0.5 1.0                  -nx,xmn, xsiz
  50 0.5 1.0                  -ny,ymn, ysiz
  1 0.5 1.0                   -nz,zmn, zsiz
  1 1 1                       -x,y and z block discretization
  4 16                        -min, max data for kriging
  4                           -max per octant (0-> not used)
  400.0 200.0 20.0            -maximum search radii
  70.0 0.0 0.0                -angles for search ellipsoid
  1 2.302                     -0=SK,l=OK,2=non-st SK,3=exdrift
  0 0 0 0 0 0 0 0 0            -drift: x,y,z,xx,yy,zz,xy,xz,zy
  0                           -0, variable; 1, estimate trend
extdrift.dat                 -gridded file with drift/mean
  4                           - column number in gridded file
  3 0.02                      - Ni Traditional Structure and Sills
  1 0.45 70 0 0              :Structure type1, Sill 1, Strike1, Dip1, Plunge1
  30 30 7                     :Ranges major1, mid1 and minor1
  1 0.30 70 0 0              :Structure type2, Sill 2, Strike2, Dip2, Plunge2
  50 50 12                    :Ranges major2, mid2 and minor2
  1 0.23 70 0 0              :Structure type3, Sill 3, Strike3, Dip3, Plunge3
  100 75 15                   :Ranges major3, mid3 and minor3

Parameters for KT3D Actual Exploration Pattern Unfolded OK Ni Estimate

START OF PARAMETERS:
G2uNi.dat                     -file with data
  1 2 3 5 0                   - columns for X, Y, Z, var, sec var
  -1.0e21 1.0e21              - trimming limits
  2                            -option: 0=grid, 1=cross, 2=jackknife
GluG2Ni.dat                  -file with jackknife data
  1 2 3 5 0                   - columns for X,Y,Z, vr and sec var
  1                            -debugging level: 0,1,2,3
G2uNi_kt3d.dbg               -file for kriged output
G2uNi_kt3d.dat               -file for debugging output
  50 0.5 1.0                   -nx,xmn, xsiz
  50 0.5 1.0                   -ny,ymn, ysiz
  1 0.5 1.0                    -nz,zmn, zsiz
  1 1 1                        -x,y and z block discretization
  4 16                          -min, max data for kriging
  4                             -max per octant (0-> not used)
  400.0 200.0 20.0            -maximum search radii
  70.0 0.0 0.0                -angles for search ellipsoid
  1 2.302                     -0=SK,l=OK,2=non-st SK,3=exdrift
  0 0 0 0 0 0 0 0 0            -drift: x,y,z,xx,yy,zz,xy,xz,zy
  0                            -0, variable; 1, estimate trend
extdrift.dat                 -gridded file with drift/mean
  4                            - column number in gridded file
  3 0.02                      - Ni Traditional Structure and Sills
  1 0.45 70 0 0              :Structure type1, Sill 1, Strike1, Dip1, Plunge1
  30 30 7                     :Ranges major1, mid1 and minor1
  1 0.30 70 0 0              :Structure type2, Sill 2, Strike2, Dip2, Plunge2
  75 60 12                    :Ranges major2, mid2 and minor2
  1 0.23 70 0 0              :Structure type3, Sill 3, Strike3, Dip3, Plunge3
  200 75 15                   :Ranges major3, mid3 and minor3
Parameters for KT3D Alternative Exploration Pattern OK Ni Estimate

START OF PARAMETERS:

G3Ni.dat  -file with data
1 2 3 5 0  - columns for X, Y, Z, var, sec var
-1.0e21 1.0e21  - trimming limits
2  - option: 0=grid, 1=cross, 2=jackknife
G3Ni.dat  - file with jackknife data
1 2 3 5 0  - columns for X, Y, Z, var and sec var
1  - debugging level: 0,1,2,3
G3Ni_kt3d.dbg  - file for debugging output
G3Ni_kt3d.dat  - file for kriged output
50 0.5 1.0  - nx,xmn,xsiz
50 0.5 1.0  - ny,ymn,ysiz
1 0.5 1.0  - nz,zmn,zsiz
1 1 1  - x, y and z block discretization
4 16  - min, max data for kriging
4  - max per octant (0-> not used)
400.0 200.0 20.0  - maximum search radii
90.0 0.0 0.0  - angles for search ellipsoid
2 2 302  - 0=SK, 1=OK, 2=non-st SK, 3=exdrift
0 0 0 0 0 0 0 0 0  - drift: x, y, z, xx, yy, zz, xy, xz, zy
0  - 0, variable; 1, estimate trend
extdrift.dat  - gridded file with drift/mean
4  - column number in gridded file
1 0.02  - Ni Traditional Structure and Sills
1 0.45 90 0 0  - Structure type 1, Sill 1, Strike 1, Dip 1, Plunge 1
30 20 8  - Ranges major 1, mid 1 and minor 1
1 0.30 90 0 0  - Structure type 2, Sill 2, Strike 2, Dip 2, Plunge 2
65 50 12  - Ranges major 2, mid 2 and minor 2
1 0.23 90 0 0  - Structure type 3, Sill 3, Strike 3, Dip 3, Plunge 3
200 100 15  - Ranges major 3, mid 3 and minor 3

Parameters for KT3D Alternative Exploration Pattern Unfolded OK Ni Estimate

START OF PARAMETERS:

G3uNi.dat  - file with data
1 2 3 5 0  - columns for X, Y, Z, var, sec var
-1.0e21 1.0e21  - trimming limits
2  - option: 0=grid, 1=cross, 2=jackknife
G3uNi.dat  - file with jackknife data
1 2 3 5 0  - columns for X, Y, Z, var and sec var
1  - debugging level: 0,1,2,3
G3uNi_kt3d.dbg  - file for debugging output
G3uNi_kt3d.dat  - file for kriged output
50 0.5 1.0  - nx,xmn,xsiz
50 0.5 1.0  - ny,ymn,ysiz
1 0.5 1.0  - nz,zmn,zsiz
1 1 1  - x, y and z block discretization
4 16  - min, max data for kriging
4  - max per octant (0-> not used)
400.0 200.0 20.0  - maximum search radii
90.0 0.0 0.0  - angles for search ellipsoid
2 2 302  - 0=SK, 1=OK, 2=non-st SK, 3=exdrift
0 0 0 0 0 0 0 0 0  - drift: x, y, z, xx, yy, zz, xy, xz, zy
0  - 0, variable; 1, estimate trend
extdrift.dat  - gridded file with drift/mean
4  - column number in gridded file
1 0.02  - Ni Traditional Structure and Sills
1 0.45 90 0 0  - Structure type 1, Sill 1, Strike 1, Dip 1, Plunge 1
30 20 8  - Ranges major 1, mid 1 and minor 1
1 0.30 90 0 0  - Structure type 2, Sill 2, Strike 2, Dip 2, Plunge 2
65 50 12  - Ranges major 2, mid 2 and minor 2
1 0.23 90 0 0  - Structure type 3, Sill 3, Strike 3, Dip 3, Plunge 3
200 100 15  - Ranges major 3, mid 3 and minor 3
Parameters for KT3D Actual Exploration Pattern OK Co Estimate

*******************

START OF PARAMETERS:
G2Co.dat - file with data
1 2 3 5 0 - columns for X, Y, Z, var, sec var
-1.0E21 1.0E21 - trimming limits
2 - option: 0=grid, 1=cross, 2=jackknife
G1Co.dat - file with jackknife data
1 2 3 5 0 - columns for X,Y,Z,var and sec var
1 - debugging level: 0,1,2,3
G2Co_kt3d.dbg - file for debugging output
G2Co_kt3d.dat - file for kriged output
50 0.5 1.0 - nx,xm,xsz
50 0.5 1.0 - ny,ym,ysz
1 0.5 1.0 - nz,zm,zsz
1 1 1 - x,y and z block discretization
4 16 - min, max data for kriging
4 - max per octant (0-> not used)
4 00.0 200.0 20.0 - maximum search radii
100.0 0.0 0.0 - angles for search ellipsoid
1 2 302 - 0=SK,1=OK,2=non-st SK,3=exdrift
0 0 0 0 0 0 0 0 0 - drift: x,y,z,xx,yy,zz,xy,xz,zy
0 - variable; 1, estimate trend
extdrift.dat - gridded file with drift/mean
1 0.25 - Co Traditional Structure and Sills
1 0.40 100 0 0 : Structure type1, Sill1, Strike1, Dip1, Plunge1
602 0 6 : Ranges major1, mid1 and minor1
1 0.25 100 0 0 : Structure type2, Sill2, Strike2, Dip2, Plunge2
755 0 8 : Ranges major2, mid2 and minor2
1 0.10 100 0 0 : Structure type3, Sill3, Strike3, Dip3, Plunge3
200 150 10 : Ranges major3, mid3 and minor3

Parameters for KT3D Actual Exploration Pattern Unfolded OK Co Estimate

*******************

START OF PARAMETERS:
G2uCo.dat - file with data
1 2 3 5 0 - columns for X, Y, Z, var, sec var
-1.0E21 1.0E21 - trimming limits
2 - option: 0=grid, 1=cross, 2=jackknife
G1uG2Co.dat - file with jackknife data
1 2 3 5 0 - columns for X,Y,Z,var and sec var
1 - debugging level: 0,1,2,3
G2uCo_kt3d.dbg - file for debugging output
G2uCo_kt3d.dat - file for kriged output
50 0.5 1.0 - nx,xm,xsz
50 0.5 1.0 - ny,ym,ysz
1 0.5 1.0 - nz,zm,zsz
1 1 1 - x,y and z block discretization
4 16 - min, max data for kriging
4 - max per octant (0-> not used)
4 00.0 200.0 20.0 - maximum search radii
110.0 0.0 0.0 - angles for search ellipsoid
1 2 302 - 0=SK,1=OK,2=non-st SK,3=exdrift
0 0 0 0 0 0 0 0 0 - drift: x,y,z,xx,yy,zz,xy,xz,zy
0 - variable; 1, estimate trend
extdrift.dat - gridded file with drift/mean
1 0.20 - Co Traditional Structure and Sills
1 0.35 110 0 0 : Structure type1, Sill1, Strike1, Dip1, Plunge1
202 0 5 : Ranges major1, mid1 and minor1
1 0.25 110 0 0 : Structure type2, Sill2, Strike2, Dip2, Plunge2
755 0 8 : Ranges major2, mid2 and minor2
1 0.20 110 0 0 : Structure type3, Sill3, Strike3, Dip3, Plunge3
50 50 10 : Ranges major3, mid3 and minor3

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Parameters for KT3D Actual Exploration Pattern OK Co Estimate

*******************

START OF PARAMETERS:

G2Co.dat  - file with data
 1 2 3 5 0  - columns for X, Y, Z, var, sec var
-1.0e-21 1.0e-21  - trimming limits
 2  - option: 0=grid, 1=cross, 2=jackknife
G1Co.dat  - file with jackknife data
 1 2 3 5 0  - columns for X,Y,Z,vr and sec var
 1  - debugging level: 0,1,2,3
G2Co_kt3d.dbg  - file for debugging output
G2Co_kt3d.dat  - file for kriged output

50 0.5 1.0  - nx,xmn,xsiz
50 0.5 1.0  - ny,ymn,ysiz
1 0.5 1.0  - nz,zmn,zsiz
1 1 1  - x,y and z block discretization
4 16  - min, max data for kriging
4  - max per octant (0-> not used)
400.0 200.0 20.0  - maximum search radii
100.0 0.0 0.0  - angles for search ellipsoid
1 2.302  - 0=SK,1=OK,2=non-st, SK,3=exdrift
0 0 0 0 0 0 0 0 0  - drift: x,y,z,xx,yy,zz,xy,xz,zy
0  - 0, variable; 1, estimate trend

extdrift.dat  - gridded file with drift/mean
3 0.25  - Co Traditional Structure and Sills
1 0.40 100 0 0  - Structure type1, Sill 1, Strike1, Dip1, Plunge1
602 0 6  - Ranges major1, midi and minor1
1 0.25 100 0 0  - Structure type2, Sill 2, Strike2, Dip2, Plunge2
755 0 8  - Ranges major2, midi and minor2
1 0.10 100 0 0  - Structure type3, Sill 3, Strike3, Dip3, Plunge3
200 150 10  - Ranges major3, midi3 and minor3

Parameters for KT3D Actual Exploration Pattern Unfolded OK Co Estimate

*******************

START OF PARAMETERS:

G2uCo.dat  - file with data
 1 2 3 5 0  - columns for X, Y, Z, var, sec var
-1.0e-21 1.0e-21  - trimming limits
 2  - option: 0=grid, 1=cross, 2=jackknife
G1uG2Co.dat  - file with jackknife data
 1 2 3 5 0  - columns for X,Y,Z,vr and sec var
 1  - debugging level: 0,1,2,3
G2uCo_kt3d.dbg  - file for debugging output
G2uCo_kt3d.dat  - file for kriged output

50 0.5 1.0  - nx,xmn,xsiz
50 0.5 1.0  - ny,ymn,ysiz
1 0.5 1.0  - nz,zmn,zsiz
1 1 1  - x,y and z block discretization
4 16  - min, max data for kriging
4  - max per octant (0-> not used)
400.0 200.0 20.0  - maximum search radii
110.0 0.0 0.0  - angles for search ellipsoid
1 2.302  - 0=SK,1=OK,2=non-st, SK,3=exdrift
0 0 0 0 0 0 0 0 0  - drift: x,y,z,xx,yy,zz,xy,xz,zy
0  - 0, variable; 1, estimate trend

extdrift.dat  - gridded file with drift/mean
3 0.20  - Co Traditional Structure and Sills
1 0.35 110 0 0  - Structure type1, Sill 1, Strike1, Dip1, Plunge1
202 0 5  - Ranges major1, midi and minor1
1 0.25 110 0 0  - Structure type2, Sill 2, Strike2, Dip2, Plunge2
404 0 8  - Ranges major2, midi2 and minor2
1 0.20 110 0 0  - Structure type3, Sill 3, Strike3, Dip3, Plunge3
50 50 10  - Ranges major3, midi3 and minor3
Parameters for KT3D Alternative Exploration Pattern OK Co Estimate

START OF PARAMETERS:
G3Co.dat
- file with data
1 2 3 5 0 - columns for X, Y, Z, var, sec var
-1.0e21 1.0e21 - trimming limits
2 - option: 0=grid, 1=cross, 2=jackknife
G1Co.dat
- file with jackknife data
1 2 3 5 0 - columns for X, Y, Z, var and sec var
1 - debugging level: 0,1,2,3
G3Co_kt3d.dbg
- file for debugging output
G3Co_kt3d.dat
- file for kriged output
50 0.5 1.0 - nx, nyn, nzn
50 0.5 1.0 - nz, nzn, nzn
1 0.5 1.0 - x, y and z block discretization
4 16 - min, max data for kriging
- max per octant (0-> not used)
400.0 200.0 20.0 - maximum search radii
90.0 0.0 0.0 - angles for search ellipsoid
1 2.302 - 0=SK, 1=OK, 2=non-st, 3=exdrift
0 0 0 0 0 0 0 - drift: x, y, z, xx, yy, zz, xy, xz, yz
0 -0, variable; 1, estimate trend
extdrift.dat
- gridded file with drift/mean
4 - column number in gridded file
3 0.30 - Co Traditional Structure and Sills
1 0.30 90 0 0 - Structure type1, Sill 1, Strike1, Dip1, Plunge1
20 20 8 - Ranges major1, mid1 and minor1
1 0.20 90 0 0 - Structure type2, Sill 2, Strike2, Dip2, Plunge2
30 30 9 - Ranges major2, mid2 and minor2
1 0.20 90 0 0 - Structure type3, Sill 3, Strike3, Dip3, Plunge3
40 40 10 - Ranges major3, mid3 and minor3

Parameters for KT3D Alternative Exploration Pattern Unfolded OK Co Estimate

START OF PARAMETERS:
G3uCo.dat
- file with data
1 2 3 5 0 - columns for X, Y, Z, var, sec var
-1.0e21 1.0e21 - trimming limits
2 - option: 0=grid, 1=cross, 2=jackknife
G1uCo.dat
- file with jackknife data
1 2 3 5 0 - columns for X, Y, Z, var and sec var
1 - debugging level: 0,1,2,3
G3uCo_kt3d.dbg
- file for debugging output
G3uCo_kt3d.dat
- file for kriged output
50 0.5 1.0 - nx, nyn, nzn
50 0.5 1.0 - nz, nzn, nzn
1 0.5 1.0 - x, y and z block discretization
4 16 - min, max data for kriging
- max per octant (0-> not used)
400.0 200.0 20.0 - maximum search radii
90.0 0.0 0.0 - angles for search ellipsoid
1 2.302 - 0=SK, 1=OK, 2=non-st, 3=exdrift
0 0 0 0 0 0 0 - drift: x, y, z, xx, yy, zz, xy, xz, yz
0 -0, variable; 1, estimate trend
extdrift.dat
- gridded file with drift/mean
4 - column number in gridded file
3 0.25 - Co Traditional Structure and Sills
1 0.30 90 0 0 - Structure type1, Sill 1, Strike1, Dip1, Plunge1
20 20 7 - Ranges major1, mid1 and minor1
1 0.25 90 0 0 - Structure type2, Sill 2, Strike2, Dip2, Plunge2
50 30 8 - Ranges major2, mid2 and minor2
1 0.20 90 0 0 - Structure type3, Sill 3, Strike3, Dip3, Plunge3
100 40 12 - Ranges major3, mid3 and minor3
Parameters for IK3D Actual Exploration Pattern IK Ni Estimate

START OF PARAMETERS:
- 1=continuous (cdf), 0=categorical (pdf)
- option: O=grid, 1=cross, 2=jackknife
- columns for X,Y,Z,VR
- number thresholds/categories
- global cdf/pdf
- file with jackknife data
- columns for X,Y,Z and variable
- file with soft indicator input
- trimming limits
- debugging level: 0,1,2,3
- file for debugging output
- file for kriging output
- ruc,xmn,xsiz
- ny,ymn,ysiz
- nz,zrnn,zsiz
- min, max data for kriging
- maximum search radii
- angles for search ellipsoid
- max per octant (0-> not used)
- 0=full IK, 1=Median IK(threshold num)
- 1=OK

0.5 Ni pct Grade Threshold and 26.6 Percentile
0.6 Ni pct Grade Threshold and 36.8 Percentile
0.7 Ni pct Grade Threshold and 46 Percentile
0.8 Ni pct Grade Threshold and 55.2 Percentile
0.9 Ni pct Grade Threshold and 63.7 Percentile
1.0 Ni pct Grade Threshold and 71.8 Percentile
1.1 Ni pct Grade Threshold and 78.9 Percentile
1.2 Ni pct Grade Threshold and 85.1 Percentile
1.3 Ni pct Grade Threshold and 92.2 Percentile
1.4 Ni pct Grade Threshold and 99.3 Percentile
1.5 Ni pct Grade Threshold and 106.4 Percentile
1.6 Ni pct Grade Threshold and 113.5 Percentile

0.5 Ni pct Grade Threshold and 26.6 Percentile
0.6 Ni pct Grade Threshold and 36.8 Percentile
0.7 Ni pct Grade Threshold and 46 Percentile
0.8 Ni pct Grade Threshold and 55.2 Percentile
0.9 Ni pct Grade Threshold and 63.7 Percentile
1.0 Ni pct Grade Threshold and 71.8 Percentile
1.1 Ni pct Grade Threshold and 78.9 Percentile
1.2 Ni pct Grade Threshold and 85.1 Percentile
1.3 Ni pct Grade Threshold and 92.2 Percentile
1.4 Ni pct Grade Threshold and 99.3 Percentile
1.5 Ni pct Grade Threshold and 106.4 Percentile
1.6 Ni pct Grade Threshold and 113.5 Percentile
Parameters for POSTIK Actual Exploration Pattern IK Co E-type estimate

START OF PARAMETERS:

1 0.20 70 0 0 :Structure type2, Sill 2, Strike2, Dip2, Plunge2
1 0.20 70 0 0 :Ranges major2, mid2 and minor2
1 0.20 70 0 0 :Ranges major3, mid3 and minor3
3 0.30 1.2 Ni pct Grade Threshold and 84.7 Percentile
1 0.30 90 0 0 :Structure type1, Sill 1, Strike1, Dip1, Plunge1
1 0.20 70 0 0 :Ranges major1, mid1 and minor1
1 0.20 70 0 0 :Ranges major2, mid2 and minor2
1 0.20 70 0 0 :Ranges major3, mid3 and minor3
3 0.30 1.3 Ni pct Grade Threshold and 89.3 Percentile
1 0.30 90 0 0 :Structure type1, Sill 1, Strike1, Dip1, Plunge1
1 0.20 70 0 0 :Ranges major1, mid1 and minor1
1 0.20 70 0 0 :Ranges major2, mid2 and minor2
1 0.20 70 0 0 :Ranges major3, mid3 and minor3
3 0.30 1.4 Ni pct Grade Threshold and 93 Percentile
1 0.30 90 0 0 :Structure type1, Sill 1, Strike1, Dip1, Plunge1
1 0.20 70 0 0 :Ranges major1, mid1 and minor1
1 0.20 70 0 0 :Ranges major2, mid2 and minor2
1 0.20 70 0 0 :Ranges major3, mid3 and minor3
3 0.30 1.5 Ni pct Grade Threshold and 95.5 Percentile
1 0.30 90 0 0 :Structure type1, Sill 1, Strike1, Dip1, Plunge1
1 0.20 70 0 0 :Ranges major1, mid1 and minor1
1 0.20 70 0 0 :Ranges major2, mid2 and minor2
1 0.20 70 0 0 :Ranges major3, mid3 and minor3
3 0.30 1.6 Ni pct Grade Threshold and 97.2 Percentile
1 0.30 100 0 0 :Structure type1, Sill 1, Strike1, Dip1, Plunge1
3 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 -the thresholds
0 1 0.75 -volume support?, type, varied
0 1 0.75 -file with global distribution
3 0 -1.0 1.0e21 -ivr, ivr, min, max
0.05 2.7 -minimum and maximum Z value
2 1.5 -lower tail: option, parameter
1 1.0 -middle : option, parameter
4 1.5 -upper tail: option, parameter
500 -maximum discretization

option 1 = E-type
2 = probability and mean above threshold(par)
3 = 2 percentile corresponding to (par)
4 = conditional variance
### Parameters for IK3D Actual Exploration Pattern Unfolded

#### START OF PARAMETERS:

1. **-l=continuous (cdf), -o=categorical (pdf)**
2. **-option: 0=grid, 1=cross, 2=jackknife**
3. **GluG2Ni.dat**
4. **-file with jackknife data**
5. **1 2 3 5**
6. **- columns for X,Y,Z,vr**
7. **0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 - thresholds / categories**
8. **0.266 0.368 0.460 0.552 0.637 0.718 0.789 0.847 0.893 0.930 0.955 0.972 - global cdf / pdf**
9. **G2uNi.dat**
10. **-file with data**
11. **direct.ik**
12. **-file with soft indicator input**
13. **1 2 O 3 4 5 6 columns for X,Y,Z and indicators**
14. **-l.Oe21 l.Oe21 -trimming limits**
15. **2 -debugging level: 0,1,2,3**
16. **G2uNi_ik3d.dbg**
17. **-file for debugging output**
18. **G2uNi_ik3d.dat**
19. **-file for kriging output**
20. **10 2.5 5.0 -nx,xmn,xsiz**
21. **10 2.5 5.0 -ny,ymn,ysiz**
22. **4**
23. **152**

#### Table of Parameters:

<table>
<thead>
<tr>
<th>Threshold (Ni pct Grade)</th>
<th>Structure Type 1</th>
<th>Sill 1</th>
<th>Strike 1</th>
<th>Dip 1</th>
<th>Plunge 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.25</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.6</td>
<td>0.35</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.7</td>
<td>0.45</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.8</td>
<td>0.55</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.9</td>
<td>0.65</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

#### Categories:

1. **0.20 30.0 0.0 0**
2. **0.20 30.0 0.0 0**
3. **0.20 30.0 0.0 0**
4. **0.20 30.0 0.0 0**
5. **0.20 30.0 0.0 0**

#### Options:

- **-l=continuous (cdf), -o=categorical (pdf)**
- **-option: 0=grid, 1=cross, 2=jackknife**
- **-file with jackknife data**
- **- columns for X,Y,Z,vr**
- **- thresholds / categories**
- **-global cdf / pdf**
- **-file with data**
- **-file with soft indicator input**
- **-columns for X,Y,Z and indicators**
- **-trimming limits**
- **-debugging level: 0,1,2,3**
- **-file for debugging output**
- **-file for kriging output**
- **-nx,xmn,xsiz**
- **-ny,ymn,ysiz**
- **-angles for search ellipsoid**
- **-max per octant (0-> not used)**
- **-0=full IK, 1=Median IK (threshold num)**
- **-0=SK, 1=OK**

---

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Parameters for POSTIK Actual Exploration Pattern Unfolded IK Ni E-Type Estimate

***************

START OF PARAMETERS:

G2uNi_ik3d.dat - file with IK3D output (continuous)
G2uNi_postik.dat - file for output
1 0.35 - output option, output parameter
12 - number of thresholds
0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 - the thresholds
0 1 - 0.75 - volume support?, type, varied
cluster.dat - file with global distribution
0 0 - 1.0 1.0e21 - minimum and maximum Z value
3 0 - 1.5 - lower tail: option, parameter
1 1.0 - middle: option, parameter
4 1.5 - upper tail: option, parameter
500 - maximum discretization

option 1 = E-type
2 = probability and mean above threshold (par)
3 = Z percentile corresponding to (par)
4 = conditional variance

1 0.30 90 0 0 : Structure type 1, Sill 1, Strike 1, Dip 1, Plunge 1
1 0.20 90 0 0 : Structure type 2, Sill 2, Strike 2, Dip 2, Plunge 2
1 0.20 90 0 0 : Structure type 3, Sill 3, Strike 3, Dip 3, Plunge 3
3 0.30 90 0 0 : 1.2 Ni pct Grade Threshold and 94.7 Percentile
1 0.30 90 0 0 : Structure type 1, Sill 1, Strike 1, Dip 1, Plunge 1
20 15 7 : Ranges major 1, mid 1 and minor 1
1 0.20 90 0 0 : Structure type 2, Sill 2, Strike 2, Dip 2, Plunge 2
75 20 10 : Ranges major 2, mid 2 and minor 2
1 0.20 90 0 0 : Structure type 3, Sill 3, Strike 3, Dip 3, Plunge 3
125 30 12 : Ranges major 3, mid 3 and minor 3
3 0.30 90 0 0 : 1.3 Ni pct Grade Threshold and 89.3 Percentile
1 0.30 90 0 0 : Structure type 1, Sill 1, Strike 1, Dip 1, Plunge 1
20 15 7 : Ranges major 1, mid 1 and minor 1
1 0.20 90 0 0 : Structure type 2, Sill 2, Strike 2, Dip 2, Plunge 2
75 20 10 : Ranges major 2, mid 2 and minor 2
1 0.20 90 0 0 : Structure type 3, Sill 3, Strike 3, Dip 3, Plunge 3
100 30 12 : Ranges major 3, mid 3 and minor 3
3 0.30 90 0 0 : 1.4 Ni pct Grade Threshold and 93 Percentile
1 0.30 90 0 0 : Structure type 1, Sill 1, Strike 1, Dip 1, Plunge 1
20 15 7 : Ranges major 1, mid 1 and minor 1
1 0.20 90 0 0 : Structure type 2, Sill 2, Strike 2, Dip 2, Plunge 2
70 20 9 : Ranges major 2, mid 2 and minor 2
1 0.20 90 0 0 : Structure type 3, Sill 3, Strike 3, Dip 3, Plunge 3
80 30 10 : Ranges major 3, mid 3 and minor 3
3 0.30 90 0 0 : 1.5 Ni pct Grade Threshold and 95.5 Percentile
1 0.30 90 0 0 : Structure type 1, Sill 1, Strike 1, Dip 1, Plunge 1
20 15 7 : Ranges major 1, mid 1 and minor 1
1 0.20 90 0 0 : Structure type 2, Sill 2, Strike 2, Dip 2, Plunge 2
40 20 8 : Ranges major 2, mid 2 and minor 2
1 0.20 90 0 0 : Structure type 3, Sill 3, Strike 3, Dip 3, Plunge 3
50 30 9 : Ranges major 3, mid 3 and minor 3
3 0.30 90 0 0 : 1.6 Ni pct Grade Threshold and 97.2 Percentile
1 0.30 90 0 0 : Structure type 1, Sill 1, Strike 1, Dip 1, Plunge 1
20 15 6 : Ranges major 1, mid 1 and minor 1
1 0.20 90 0 0 : Structure type 2, Sill 2, Strike 2, Dip 2, Plunge 2
40 20 7 : Ranges major 2, mid 2 and minor 2
1 0.20 90 0 0 : Structure type 3, Sill 3, Strike 3, Dip 3, Plunge 3
50 30 8 : Ranges major 3, mid 3 and minor 3

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Parameters for IK3D Alternative Exploration Pattern IK Ni Estimate

START OF PARAMETERS:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLNi.dat</td>
<td>1 2 3 5</td>
</tr>
<tr>
<td>- option:</td>
<td></td>
</tr>
<tr>
<td>- columns for X,Y,Z,vr</td>
<td></td>
</tr>
<tr>
<td>- number thresholds/categories</td>
<td>0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6</td>
</tr>
<tr>
<td>- thresholds / categories</td>
<td></td>
</tr>
<tr>
<td>0.261 Ni pct Grade Threshold and 38.7 Percentile</td>
<td>0 : Structure type 1, Sill 1, Strike 1, Dip 1, Plunge 1</td>
</tr>
<tr>
<td>0 : Structure type 2, Sill 2, Strike 2, Dip 2, Plunge 2</td>
<td></td>
</tr>
<tr>
<td>0 : Structure type 3, Sill 3, Strike 3, Dip 3, Plunge 3</td>
<td></td>
</tr>
<tr>
<td>0 : Structure type 4, Sill 4, Strike 4, Dip 4, Plunge 4</td>
<td></td>
</tr>
<tr>
<td>0 : Structure type 5, Sill 5, Strike 5, Dip 5, Plunge 5</td>
<td></td>
</tr>
<tr>
<td>0 : Structure type 6, Sill 6, Strike 6, Dip 6, Plunge 6</td>
<td></td>
</tr>
<tr>
<td>0 : Structure type 7, Sill 7, Strike 7, Dip 7, Plunge 7</td>
<td></td>
</tr>
<tr>
<td>0 : Structure type 8, Sill 8, Strike 8, Dip 8, Plunge 8</td>
<td></td>
</tr>
<tr>
<td>0 : Structure type 9, Sill 9, Strike 9, Dip 9, Plunge 9</td>
<td></td>
</tr>
<tr>
<td>0 : Structure type 10, Sill 10, Strike 10, Dip 10, Plunge 10</td>
<td></td>
</tr>
</tbody>
</table>

-1 = continuous (cdf), 0=categorical (pdf)
- option: O=grid, 1=cross, 2=jackknife
- file with jackknife data
- trimming limits
- debugging level: 0, 1, 2, 3
- file for debugging output
- file for kriging output
- nx, nxm, xsiz
- ny, nym, ysz
- nz, nzm, zsz
- min, max data for kriging
- angles for search ellipsoid
- max per octant (0-> not used)
- debug: 0=full IK, 1=Median IK (threshold num)
- O=full IK, 1=Median IK (threshold num)

<table>
<thead>
<tr>
<th>Column</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DH, X, Y, Z and variable</td>
<td></td>
</tr>
<tr>
<td>columns for DH, X, Y, Z and indicators</td>
<td></td>
</tr>
<tr>
<td>- trimming limits</td>
<td></td>
</tr>
<tr>
<td>- debugging level: 0, 1, 2, 3</td>
<td></td>
</tr>
<tr>
<td>- file for debugging output</td>
<td></td>
</tr>
<tr>
<td>- file for kriging output</td>
<td></td>
</tr>
<tr>
<td>- nx, nxm, xsiz</td>
<td></td>
</tr>
<tr>
<td>- ny, nym, ysz</td>
<td></td>
</tr>
<tr>
<td>- nz, nzm, zsz</td>
<td></td>
</tr>
<tr>
<td>- min, max data for kriging</td>
<td></td>
</tr>
<tr>
<td>- angles for search ellipsoid</td>
<td></td>
</tr>
<tr>
<td>- max per octant (0-&gt; not used)</td>
<td></td>
</tr>
<tr>
<td>- debug: 0=full IK, 1=Median IK (threshold num)</td>
<td></td>
</tr>
<tr>
<td>- O=full IK, 1=Median IK (threshold num)</td>
<td></td>
</tr>
</tbody>
</table>

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### Parameters for POSTIK Alternative Exploration Pattern Ni E-Type Estimate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni pct Grade Threshold and 80.6 Percentile</td>
<td>0.25</td>
<td>Structure type 1, Sill 1, Strike 1, Dip 1, Plunge 1</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>Ranges major 1, mid 1 and minor 1</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>Structure type 1, Sill 2, Strike 2, Dip 2, Plunge 2</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Ranges major 2, mid 2 and minor 2</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Structure type 1, Sill 3, Strike 3, Dip 3, Plunge 3</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>Ranges major 3, mid 3 and minor 3</td>
</tr>
<tr>
<td>Ni pct Grade Threshold and 85.6 Percentile</td>
<td>0.30</td>
<td>Structure type 2, Sill 1, Strike 1, Dip 1, Plunge 1</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>Ranges major 1, mid 1 and minor 1</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Structure type 2, Sill 2, Strike 2, Dip 2, Plunge 2</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Ranges major 2, mid 2 and minor 2</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>Structure type 2, Sill 3, Strike 3, Dip 3, Plunge 3</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>Ranges major 3, mid 3 and minor 3</td>
</tr>
<tr>
<td>Ni pct Grade Threshold and 88.7 Percentile</td>
<td>0.35</td>
<td>Structure type 3, Sill 1, Strike 1, Dip 1, Plunge 1</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>Ranges major 1, mid 1 and minor 1</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>Structure type 3, Sill 2, Strike 2, Dip 2, Plunge 2</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>Ranges major 2, mid 2 and minor 2</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>Structure type 3, Sill 3, Strike 3, Dip 3, Plunge 3</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>Ranges major 3, mid 3 and minor 3</td>
</tr>
<tr>
<td>Ni pct Grade Threshold and 92.5 Percentile</td>
<td>0.40</td>
<td>Structure type 4, Sill 1, Strike 1, Dip 1, Plunge 1</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>Ranges major 1, mid 1 and minor 1</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>Structure type 4, Sill 2, Strike 2, Dip 2, Plunge 2</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>Ranges major 2, mid 2 and minor 2</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>Structure type 4, Sill 3, Strike 3, Dip 3, Plunge 3</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>Ranges major 3, mid 3 and minor 3</td>
</tr>
<tr>
<td>Ni pct Grade Threshold and 94.2 Percentile</td>
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<td>Structure type 5, Sill 1, Strike 1, Dip 1, Plunge 1</td>
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<tr>
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<td>0.45</td>
<td>Ranges major 1, mid 1 and minor 1</td>
</tr>
<tr>
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<td>0.45</td>
<td>Structure type 5, Sill 2, Strike 2, Dip 2, Plunge 2</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>Ranges major 2, mid 2 and minor 2</td>
</tr>
<tr>
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<td>0.45</td>
<td>Structure type 5, Sill 3, Strike 3, Dip 3, Plunge 3</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>Ranges major 3, mid 3 and minor 3</td>
</tr>
<tr>
<td>Ni pct Grade Threshold and 96.4 Percentile</td>
<td>0.60</td>
<td>Structure type 6, Sill 1, Strike 1, Dip 1, Plunge 1</td>
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<tr>
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<td>0.50</td>
<td>Ranges major 1, mid 1 and minor 1</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>Structure type 6, Sill 2, Strike 2, Dip 2, Plunge 2</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>Ranges major 2, mid 2 and minor 2</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>Structure type 6, Sill 3, Strike 3, Dip 3, Plunge 3</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>Ranges major 3, mid 3 and minor 3</td>
</tr>
</tbody>
</table>

### START OF PARAMETERS:

```
G3Ni_ik3d.dat
G3Ni_postik.dat
1 0.25
12
0.5 0.6 0.7 0.8
-the thresholds
0 1 0.75
cluster.dat
3 0 -1.0 1.0e21
0.05 2.7
2 1.5
1 1.5
4 1.5
500
```

Option 1 = E-type
2 = probability and mean above threshold (par)
3 = Z percentile corresponding to (par)
4 = conditional variance
Parameters for IK3D: Alternative Exploration Pattern Unfolded

START OF PARAMETERS:

1 1 =Continuous(cdf), 0 =categorical(pdf)
2 -option: 0 =grid, 1 =cross, 2 =jackknife
GluG3Ni.dat -file with jackknife data
1 2 3 5 - columns for X,Y,Z,VR
12 - number thresholds/categories
0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 - thresholds / categories
0.261 0.387 0.473 0.570 0.664 0.748 0.806 0.856 0.887 0.923 0.942 0.964 - global cdf / pdf
G3uNi.dat -file with data
4 1 2 3 5 - columns for X,Y,Z and variable
direct.ik -file with soft indicator input
1 2 0 3 4 5 6 - columns for X,Y,Z and indicators
-1.0e21 1.0e21 - trimming limits
2 -debugging level: 0, 1, 2, 3
G3uNi_ik3d.dbg -file for debugging output
G3uNi_ik3d.dat -file for kriging output
4 1 2 3 0.5 Ni pct Grade Threshold and 26.1 Percentile
10 2.5 5.0 - file for search ellipsoid
80.0 100.0 20.0 - maximum search radii
90.0 0.0 0.0 - angles for search ellipsoid
4 -max per octant (0 -> not used)
1 2.5 -0 =full IK, 1 =Median IK (threshold num)
1 -0 =OK, 1 =OK
3 0.25 0.5 Ni pct Grade Threshold and 26.1 Percentile
1 0.35 90 0 0 0 - Structure type1, Sill 1, Strike1, Dip1, Plunge1
30 30 5 - Ranges major1, mid1 and minor1
2 0.20 90 0 0 0 - Structure type2, Sill 2, Strike2, Dip2, Plunge2
50 50 8 - Ranges major2, mid2 and minor2
1 0.20 90 0 0 0 - Structure type3, Sill 3, Strike3, Dip3, Plunge3
100 100 10 - Ranges major3, mid3 and minor3
3 0.20 0.6 Ni pct Grade Threshold and 38.7 Percentile
1 0.35 90 0 0 0 - Structure type1, Sill 1, Strike1, Dip1, Plunge1
50 40 6 - Ranges major1, mid1 and minor1
1 0.20 90 0 0 0 - Structure type2, Sill 2, Strike2, Dip2, Plunge2
60 60 8 - Ranges major2, mid2 and minor2
1 0.25 90 0 0 0 - Structure type3, Sill 3, Strike3, Dip3, Plunge3
100 100 10 - Ranges major3, mid3 and minor3
3 0.20 0.7 Ni pct Grade Threshold and 47.3 Percentile
1 0.35 90 0 0 0 - Structure type1, Sill 1, Strike1, Dip1, Plunge1
40 40 6 - Ranges major1, mid1 and minor1
1 0.20 90 0 0 0 - Structure type2, Sill 2, Strike2, Dip2, Plunge2
50 50 10 - Ranges major2, mid2 and minor2
1 0.25 90 0 0 0 - Structure type3, Sill 3, Strike3, Dip3, Plunge3
120 60 12 - Ranges major3, mid3 and minor3
3 0.20 0.8 Ni pct Grade Threshold and 57 Percentile
1 0.35 90 0 0 0 - Structure type1, Sill 1, Strike1, Dip1, Plunge1
40 30 6 - Ranges major1, mid1 and minor1
1 0.20 90 0 0 0 - Structure type2, Sill 2, Strike2, Dip2, Plunge2
50 40 10 - Ranges major2, mid2 and minor2
1 0.25 90 0 0 0 - Structure type3, Sill 3, Strike3, Dip3, Plunge3
100 60 14 - Ranges major3, mid3 and minor3
3 0.20 0.9 Ni pct Grade Threshold and 66.4 Percentile
1 0.35 90 0 0 0 - Structure type1, Sill 1, Strike1, Dip1, Plunge1
40 20 6 - Ranges major1, mid1 and minor1
1 0.20 90 0 0 0 - Structure type2, Sill 2, Strike2, Dip2, Plunge2
50 30 12 - Ranges major2, mid2 and minor2
1 0.25 90 0 0 0 - Structure type3, Sill 3, Strike3, Dip3, Plunge3
80 60 18 - Ranges major3, mid3 and minor3
3 0.20 1 Ni pct Grade Threshold and 74.8 Percentile
1 0.35 90 0 0 0 - Structure type1, Sill 1, Strike1, Dip1, Plunge1
40 20 5 - Ranges major1, mid1 and minor1
1 0.20 90 0 0 0 - Structure type2, Sill 2, Strike2, Dip2, Plunge2
50 30 14 - Ranges major2, mid2 and minor2
1 0.25 90 0 0 0 - Structure type3, Sill 3, Strike3, Dip3, Plunge3
80 60 18 - Ranges major3, mid3 and minor3
3 0.20 1.1 Ni pct Grade Threshold and 80.6 Percentile
1 0.35 90 0 0 0 - Structure type1, Sill 1, Strike1, Dip1, Plunge1
Parameters for POSTIK Alternative Exploration Pattern Unfolded IK Ni E-Type Estimate

START OF PARAMETERS:
G3uNi_ik3d.dat  
G3uNi_postik.dat  
1 0.25  
12 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6  
G3uNi_postik.dat  
-1.0 1.0e21  
0.05 2.7  
-ivr, iwt, tmin, tmax  
0 1.0  
3 0.75  
-cluster.dat  
3 0  
-ir, iwt, tmin, tmax  
2 1.5  
1 1.0  
4 1.5  
500  

option 1 = E-type  
2 = probability and mean above threshold(par)  
3 = Z percentile corresponding to (par)  
4 = conditional variance

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Parameters for IK3D Actual Exploration Pattern IK Co Estimate

START OF PARAMETERS:

-1=continuous(cdf), 0=categorical(pdf)
-option: 0=grid, 1=cross, 2=jackknife

G1Co.dat - file with jackknife data
- columns for X,Y,Z,vr
- number thresholds/categories

0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10 0.11 0.12 0.13
0.34

0.363 0.548 0.738 0.788 0.828 0.862 0.896 0.914 0.927 5.940

G2Co.dat - file with data
- columns for X,Y,Z and variable
- columns for X,Y,Z and indicators
- trimming limits
- debugging level: 0,1,2,3

- file for debugging output
- file for kriging output
- max per octant (0-> not used)

0.05 Co% Grade Threshold and 36.3 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.04 Co% Grade Threshold and 54.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.03 Co% Grade Threshold and 36.3 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.02 Co% Grade Threshold and 65.9 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.01 Co% Grade Threshold and 73.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.00 Co% Grade Threshold and 78.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.09 Co% Grade Threshold and 86.2 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.08 Co% Grade Threshold and 82.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.07 Co% Grade Threshold and 78.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.06 Co% Grade Threshold and 73.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.05 Co% Grade Threshold and 65.9 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.04 Co% Grade Threshold and 54.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.03 Co% Grade Threshold and 36.3 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.02 Co% Grade Threshold and 65.9 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.01 Co% Grade Threshold and 73.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

0.00 Co% Grade Threshold and 78.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

- full IK, 1=Median IK(threshold num)

- file for soft indicator input
- columns for DH,X,Y,Z and variable
- file with soft indicator input
- columns for X,Y,Z and indicators

- trimming limits
- debugging level: 0,1,2,3

- file for debugging output
- file for kriging output
- max per octant (0-> not used)

- number thresholds/categories
- columns for X,Y,Z,vr

10 2.1 2.5 4 5 6
1.0e21
-1.0e21

GZCo.dat
GZCo_ik3d.dbg
GZCo_ik3d.dat

10 2.5 5.0
10 2.5 5.0
1 0.0 5.0

4 1 2 3 5
direct.ik

400.0 300.0 20.0
90.0 0.0 0.0

-0.06 Co% Grade Threshold and 73.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

-0.05 Co% Grade Threshold and 65.9 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

-0.04 Co% Grade Threshold and 54.8 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3

-0.03 Co% Grade Threshold and 36.3 Percentile
0 : Structure type1, Sill 1, Strikel, Dipl, Plunge1
6 : Ranges major1, mid1 and minor1
9 : Ranges major2, mid2 and minor2
15 : Ranges major3, mid3 and minor3
Parameters for POSTIK Actual Exploration Pattern E-type Co Estimate

START OF PARAMETERS:

G2Co_ik3d.dat -file with IK3D output (continuous)
G2Co_postik.dat -file for output
1 0.25 -output option, output parameter
12 -number of thresholds
0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10 0.11 0.12 0.13 0.14 -volume support?, type, varred
cluster.dat -file with global distribution
3 0 -1.0 1.0e21 - ivr, iwt, tmin, tmax
0.001 0.90 -minimum and maximum Z value
2 1.5 -lower tail: option, parameter
1 1.0 -middle : option, parameter
4 1.5 -upper tail: option, parameter
500 -maximum discretization

option 1 = E-type
2 = probability and mean above threshold(par)
3 = Z percentile corresponding to (par)
4 = conditional variance
Parameters for IK3D Actual Exploration Pattern Unfolded IK Co Estimate

START OF PARAMETERS:

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<th>Value</th>
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<td>16</td>
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</table>

- l=continuous(cdf), O=categorical(pdf)
- option: O=grid, l=cross, 2=jackknife
- file with jackknife data
- columns for X,Y,Z,vr
- number thresholds/categories
- file with soft indicator input
- file with data
- file with soft indicator output
- trimming limits
- debugging level: 0,1,2,3
- file for debugging output
- file for kriging output
- file for kriging output
- nx,xmn,xsiz
- ny,ymn,ysiz
- nx,zmn,zsiz
- min, max data for kriging
- maximum search radii
- angles for search ellipsoid
- max per octant (0-> not used)
- O=full IK, l=Median IK(threshold num)
- O=OK

0.03 Co% Grade Threshold and 36.3 Percentile
0.04 Co% Grade Threshold and 54.8 Percentile
0.05 Co% Grade Threshold and 65.9 Percentile
0.06 Co% Grade Threshold and 73.8 Percentile
0.07 Co% Grade Threshold and 78.8 Percentile
0.08 Co% Grade Threshold and 61.8 Percentile
0.09 Co% Grade Threshold and 68.2 Percentile

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<table>
<thead>
<tr>
<th>Structure Type</th>
<th>Sill</th>
<th>Strike</th>
<th>Dip</th>
<th>Plunge</th>
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<td>0</td>
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<td>2</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
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<td>0.35</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>6</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Ranges major, mid and minor

Parameters for POSTIK Actual Exploration Pattern Unfolded E-Type Co Estimate

START OF PARAMETERS:

- G2uCo_ik3d.dat - file with IK3D output (continuous)
- G2uCo_postik.dat - file for output
- Output option, output parameter - number of thresholds
- 12
- 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10 0.11 0.12 0.13
- Volume support, type, varied - file with global distribution
- Cluster.dat
- 0 1 0.75
- 3 0 -1.0 1.0e21
- 0.001 0.90
- 2 1.5
- 1 1.0
- 4 1.5
- 500

Option 1 = E-type
2 = Probability and mean above threshold (par)
3 = 2 percentile corresponding to (par)
4 = Conditional variance
START OF PARAMETERS:

1 -I=continuous(cdf), 0=categorical(pdf)
2 -option: 0=grid, 1=cross, 2=jackknife
G1Co.dat -file with jackknife data
1 2 3 5 -columns for X,Y,Z,vr
12 -number thresholds/categories
0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10 0.11 0.12 0.13
0.399 0.534 0.654 0.737 0.794 0.843 0.865 0.899 0.920 0.931 0.948

0.986 G1Co.dat -file with data
4 1 2 3 5 -columns for DS,X,Y,Z and variable
direct.ik -file with soft indicator input
1 2 0 3 4 5 6 -columns for X,Y,Z and indicators
-1.0e21 1.0e21 -trimming limits
2 -debugging level: 0,1,2,3
G3Co_ik3d.dbg -file for debugging output
G3Co_ik3d.dat -file for kriging output
10 2.5 5.0 -nx,xmm,xaiz
10 2.5 5.0 -ny,ymn,ysiz
1 0.0 5.0 -nz,zmn,zsiz
4 16 -min, max data for kriging
400.0 300.0 20.0 -maximum search radii
90.0 0.0 0.0 -angles for search ellipsoid
4 -max per octant (0-> not used)
1 2.5 -0=full IK, 1=Median IK(threshold num)
1 -0=SK, 1=OK
3 0.15 0.03 Co% Grade Threshold and 39.9 Percentile
1 0.35 90 90 0 0 -Structure type1, Sill 1, Strike1, Dip1, Plunge1
20 15 6 -Ranges major1, mid1 and minor1
1 0.25 90 0 0 -Structure type2, Sill 2, Strike2, Dip2, Plunge2
40 20 10 -Ranges major2, mid2 and minor2
1 0.25 90 0 0 -Structure type3, Sill 3, Strike3, Dip3, Plunge3
60 50 14 -Ranges major3, mid3 and minor3
3 0.20 0.04 Co% Grade Threshold and 53.4 Percentile
1 0.35 90 90 0 0 -Structure type1, Sill 1, Strike1, Dip1, Plunge1
20 15 8 -Ranges major1, mid1 and minor1
1 0.25 90 0 0 -Structure type2, Sill 2, Strike2, Dip2, Plunge2
50 20 9 -Ranges major2, mid2 and minor2
1 0.20 90 0 0 -Structure type3, Sill 3, Strike3, Dip3, Plunge3
60 50 12 -Ranges major3, mid3 and minor3
3 0.20 0.05 Co% Grade Threshold and 65.4 Percentile
1 0.35 90 0 0 -Structure type1, Sill 1, Strike1, Dip1, Plunge1
15 15 7 -Ranges major1, mid1 and minor1
1 0.25 90 0 0 -Structure type2, Sill 2, Strike2, Dip2, Plunge2
50 20 8 -Ranges major2, mid2 and minor2
1 0.20 90 0 0 -Structure type3, Sill 3, Strike3, Dip3, Plunge3
60 40 10 -Ranges major3, mid3 and minor3
3 0.20 0.06 Co% Grade Threshold and 73.7 Percentile
1 0.35 90 0 0 -Structure type1, Sill 1, Strike1, Dip1, Plunge1
15 10 6 -Ranges major1, mid1 and minor1
1 0.25 90 0 0 -Structure type2, Sill 2, Strike2, Dip2, Plunge2
50 15 8 -Ranges major2, mid2 and minor2
1 0.20 90 0 0 -Structure type3, Sill 3, Strike3, Dip3, Plunge3
60 30 10 -Ranges major3, mid3 and minor3
3 0.20 0.07 Co% Grade Threshold and 79.4 Percentile
1 0.35 90 0 0 -Structure type1, Sill 1, Strike1, Dip1, Plunge1
20 10 5 -Ranges major1, mid1 and minor1
1 0.25 90 0 0 -Structure type2, Sill 2, Strike2, Dip2, Plunge2
40 15 8 -Ranges major2, mid2 and minor2
1 0.20 90 0 0 -Structure type3, Sill 3, Strike3, Dip3, Plunge3
60 20 12 -Ranges major3, mid3 and minor3
3 0.25 0.08 Co% Grade Threshold and 84.3 Percentile
1 0.35 90 0 0 -Structure type1, Sill 1, Strike1, Dip1, Plunge1
20 10 4 -Ranges major1, mid1 and minor1
1 0.20 90 0 0 -Structure type2, Sill 2, Strike2, Dip2, Plunge2
30 15 8 -Ranges major2, mid2 and minor2
1 0.20 90 0 0 -Structure type3, Sill 3, Strike3, Dip3, Plunge3
50 20 12 -Ranges major3, mid3 and minor3
3 0.25 0.09 Co% Grade Threshold and 86.5 Percentile
1 0.35 90 0 0 -Structure type1, Sill 1, Strike1, Dip1, Plunge1
20 10 4 -Ranges major1, mid1 and minor1
1 0.20 90 0 0 -Structure type2, Sill 2, Strike2, Dip2, Plunge2
30 15 8 -Ranges major2, mid2 and minor2
1 0.20 90 0 0 -Structure type3, Sill 3, Strike3, Dip3, Plunge3
50 20 12 -Ranges major3, mid3 and minor3
3 0.25 0.09 Co% Grade Threshold and 86.5 Percentile
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Parameters for POSTIK Alternative Exploration Pattern Co E-Type Estimate

START OF PARAMETERS:
G1Co_1k3d.dat
G1Co_postik.dat
1 0.25
12
0.03 0.04 0.05 0.06
0.07 0.08 0.09 0.10 0.11 0.12 0.13
0.14
0 1 0.75
cluster.dat
3 0 -1.0 1.0e+1
0.001 0.90
2 1.5
1 1.0
4 1.5
500

option 1 = E-type
2 = probability and mean above threshold (par)
3 = Z percentile corresponding to (par)
4 = conditional variance
Parameters for IK3D Alternative Exploration Pattern Unfolded IK Co Estimate

START OF PARAMETERS:

1 2 3 5

0.03 0.04 0.05 0.06
0.14

0.399 0.534 0.654 0.737

0.906

GluG3Co.dat

- file with data
- columns for X,Y,Z, vr
- number thresholds/categories
0.07 0.08 0.09 0.10 0.11 0.12 0.13

12

GluCo.dat

- file with data
- columns for X,Y,Z and variable
- file with soft indicator input
- columns for X,Y,Z and indicators
- trimming limits
- debugging level: 0,1,2,3
- file for debugging output
- file for kriging output
- max. max data for kriging
400.0 300.0 20.0

90.0 90.0 0.0

1 2 3 5

-1.0e21 1.0e21

4

-0=full IK, 1=Median IK(threshold num)

GluCo_ik3d.dbg

- file for debugging output

GluCo_ik3d.dat

- file for kriging output

-angles for search ellipsoid

- max per octant (0-> not used)

0 7 9 12

0 4 8 11

0 4 11 15

0 4 8 12

0.03 Co% Grade Threshold and 39.9 Percentile

0.04 Co% Grade Threshold and 53.4 Percentile

0.05 Co% Grade Threshold and 65.4 Percentile

0.06 Co% Grade Threshold and 73.7 Percentile

0.07 Co% Grade Threshold and 79.4 Percentile

0.08 Co% Grade Threshold and 84.3 Percentile

0.09 Co% Grade Threshold and 86.5 Percentile

1 2 3 5

-1=continuous(cdf), 0=categorical(pdf)

- option: 0=grid, 1=cross, 2=jackknife

- file with jackknife data

- columns for X,Y,Z, vr

- number thresholds/categories

- file with data

- columns for X,Y,Z and variable

- file with soft indicator input

- columns for X,Y,Z and indicators

- trimming limits

- debugging level: 0,1,2,3

- file for debugging output

- file for kriging output

- max. max data for kriging

- angles for search ellipsoid

- max per octant (0-> not used)

-0=full IK, 1=Median IK(threshold num)

- file for debugging output

- file for kriging output

- angles for search ellipsoid

- max per octant (0-> not used)

-0=full IK, 1=Median IK(threshold num)


Parameters for POSTIK Alternative Exploration Pattern Unfolded E-Type Co Estimate

START OF PARAMETERS:

GluCo_ik3d.dat
GluCo_postik.dat

1 0.25
12
0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10 0.11 0.12 0.13

cluster.dat
0 0.75
13 0 -1.0 1.0e21
0.00 0.90
2 1.5
1 1.0
4 1.5
500

option 1 = E-type
2 = probability and mean above threshold(par)
3 = S percentile corresponding to (par)
4 = conditional variance