PRACTICAL APPLICATION OF MULTIPLE INDICATOR KRIGING AND CONDITIONAL SIMULATION TO RECOVERABLE RESOURCE ESTIMATION FOR THE HALLEY'S LATERITIC NICKEL DEPOSIT.

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Mining and Resource Technology

Abstract

The renewed interest in the evaluation and development of lateritic nickel deposits in Australia comes at a time when multiple indicator kriging (MIK) has finally achieved a level of acceptance in the gold mining industry. The application of MIK to lateritic nickel deposits presents some theoretical and practical problems not normally encountered in gold deposit modelling. These are highlighted in a case history of resource and reserve estimation for the Halley's lateritic nickel deposit.

Nickel and cobalt are spatially correlated and were modelled together using nickel as the 'mother' variable and carrying cobalt. MIK and E-type estimates for nickel and cobalt provided both selective and non-selective mining estimates. The spatial distribution of magnesium in the deposit is significantly different to that of nickel and cobalt and therefore an independent model was necessary for magnesium. Ordinary kriging (OK) was used to estimate magnesium grades and estimates were constrained by an interpreted boundary separating high and low magnesium domains (the magnesium discontinuity).

Conditional simulation was used to simulate the local variability of the grades and validate the resource model. The simulations showed that the MIK model was a very good predictor of nickel grades and volumes. They also showed that the interpreted position of the magnesium discontinuity was critical to the correct estimation of global magnesium grades and that the initial interpretation tended to place the boundary too low in the profile. The resource model was subsequently adjusted to reflect this.

For the Halley's deposit the MIK and E-type estimates were similar. This reflects the good continuity of the nickel grades. The E-type estimates have been used for mine planning work since they are much easier to process and present. The MIK estimates show the higher grades that are *expected to be achieved by selective mining. The composite MIK/OK model has proved to be a workable solution that provides a practical basis for mine design and scheduling.*

***Key Words**: geostatistics, non-linear estimation, mining, nickel, multiple indicator kriging, cobalt, magnesium, ordinary kriging, conditional simulation.*

Introduction

Estimation of recoverable resources and reserves is one of the most critical aspects of modern mining geology. The accurate assessment of the tonnage and grade of run of mine ore, inclusive of ore loss and dilution may be the difference between a healthy profitable operation and an expensive early mine closure. Geostatistics offers several methods for recoverable resource estimation and in recent years these techniques have been put to effective use, particularly in the gold mining industry. Multiple Indicator Kriging (MIK) and conditional simulation are achieving growing acceptance in Australia as practical and cost effective methods for resource estimation and grade control. Most implementations so far seem to have been for estimation of a single economic variable, such as gold.

This paper explores the practical application of these methods to the evaluation of lateritic nickel deposits. Several variables need to be considered and this introduces some theoretical and practical problems. These problems and some alternative methods of resolving them are discussed with particular reference to the lateritic nickel deposits at Ravensthorpe in Western Australia. The Ravensthorpe Nickel Project is located close to the south coast of Western Australia and is controlled by Comet Resources NL. It is currently the subject of a study into the feasibility of development as an open pit mine, with nickel-cobalt ore to be treated by pressure acid leach (PAL) technology.

Geology

The Ravensthorpe Nickel Project is located close to the southern margin of the Archaean Yilgarn Craton, within the Ravensthorpe Greenstone Belt. The project is centred on the Halley's deposit, a single tabular lateritic nickel body some 3km long and 1km wide. The deposit occurs within the Bandalup Ultramafics, a north-northwest striking, serpentinised komatiite suite with rare interflow sedimentary units (Sampson, 1998). A thick lateritic regolith is interpreted to have developed on these rocks during the Tertiary Period, and is partially preserved at the Halley's deposit.
The regolith profile has been subdivided into five principal units (Table 1).

Table 1 Summary of major subdivisions of the weathering profile at Halley's

Zone	Description
Lateritic residuum	Strongly indurated, ferruginous and siliceous duricrust and leached siliceous pedolith
Upper ferralite	Weakly to strongly indurated porous cellular quartz-goethite (-minor clay) rock above Co-Ni-Mn redox
Lower ferralite	Weakly to strongly indurated porous cellular quartz-goethite (-minor clay) rock below Co-Ni-Mn redox
Saprolite	Clay-serpentine-goethite-carbonate weathered ultramafic with local silica veining
Fresh ultramafic	Komatiitic olivine cumulate

The geochemical, mineralogical and textural characteristics of these units reflect weathering processes dominated by:

- leaching of magnesium,
- residual enrichment of immobile elements such as nickel, iron, aluminium and chromium,
- dissolution and reprecipitation of silica,
- residual and supergene enrichment of elements such as cobalt and manganese.

These processes have resulted in a geochemical profile that displays similarities to those developed in other lateritic nickel deposits, and in particular the Cawse deposit near Kalgoorlie (Brand et al, 1996). It must be emphasised, however, that each lateritic nickel deposit has its own set of geochemical, mineralogical and structural characteristics that may require different approaches to resource estimation.

Fresh, unweathered komatiitic rocks are interpreted to underlie the profile but have rarely been intersected by evaluation drilling. Most drill holes terminated in weakly weathered serpentinite in which there is no significant accumulation of nickel.

Magnesium grades are typically greater than 20% and nickel grades are less than 0.3%.

Fresh bedrock is overlain by moderately weathered saprolite in which there has been partial leaching of mobile cations such as magnesium and minor residual enrichment of nickel. Nickel grades increase rapidly above a 0.3% threshold.

The top of the saprolite is commonly marked by a rapid decrease in magnesium content and increase in iron content. This geochemical boundary, termed the magnesium discontinuity, is a redox front that marks the contact with an overlying ferralite zone. It ranges from very sharp (e.g. from less than 1% magnesium to greater than 10% magnesium across one or two sample intervals) to gradational over several metres. The decrease in magnesium grades is mirrored by a rise in Fe grades since the boundary is conformable with the base of limonite and goethite formation. The magnesium discontinuity tends to rise at the margins of the ultramafic unit probably due to the lower solubility of the marginal facies of the ultramafic unit compared to the central facies.

The ferralite zone consists dominantly of iron oxyhydroxides, silica and minor clays. The ferralite zone is highly porous due to the relatively isovolumetric leaching of almost all of the magnesium. It is generally enriched in nickel, locally enriched in cobalt and hosts the majority of the Halley's deposit.

The ferralite zone is overlain by leached siliceous pedolith and lateritic residuum that are largely depleted in nickel, cobalt and magnesium but enriched in silica, iron and aluminium.

The nickel enrichment zone forms a single gently undulating slab. Approximately two thirds of the zone occurs within the ferralite horizon and the remaining third occurs within the saprolite. Within the enrichment zone higher nickel grades tend to occur at one or two horizons. The most continuous of the high grade zones occurs towards the top of the ferralite and is associated with the main zone of cobalt enrichment, although the peak cobalt grades typically occur 2m to 4m higher in the profile than the peak nickel grades. The cobalt mineralisation is strongly associated with manganese accumulation and is interpreted to be controlled by a redox front. A second deeper zone of higher grade nickel mineralisation is also often present and is commonly associated with the magnesium discontinuity.

Drill hole data.

The Halley's deposit has been tested by over one thousand Reverse Circulation drill holes drilled on a regular 50m by 40m grid. All holes were vertical and were sampled at 2m intervals. Samples were riffle split and were assayed using a four acid digest and ICPOES finish. Sampling and assaying quality were monitored by field re-splits, inter laboratory check analyses, assessment of standard sample assay results and twinned core drill holes. All results were satisfactory.

Selection of resource modelling method

The Halley's deposit is being considered for development as an open pit mine, with the ore to be treated by pressure acid leach (PAL). There are three principal elements of interest; nickel, cobalt and magnesium. Nickel is the main ore element but cobalt also occurs in potentially economic quantities. Magnesium is the most important gangue component in the ore because it is the principal consumer of sulphuric acid in the PAL circuit. There is therefore a direct relationship between magnesium grade and operating cost.

Ideally, the resource model should honour the local grade variability whilst also reflecting any strong geological boundaries within the deposit. Constraining the resource estimates within boundaries defined by economic cut-off grades would produce unrealistically sharp divisions between 'ore' and 'waste', since there are no natural nickel grade boundaries within the enrichment zone. Such an approach would also effectively remove the flexibility to evaluate the resource model at different cut-off grades. This flexibility is important because optimisation of the life of mine schedule may require a variable cut-off grade strategy and, in any case, the optimum cut-off grade is unlikely to be known at the time of the resource estimation.

Examination of the drill hole sections indicated that for the estimation of nickel, cobalt and magnesium grades the most significant, and strongest, boundaries correspond to the major changes in geochemical gradients within the weathering profile:

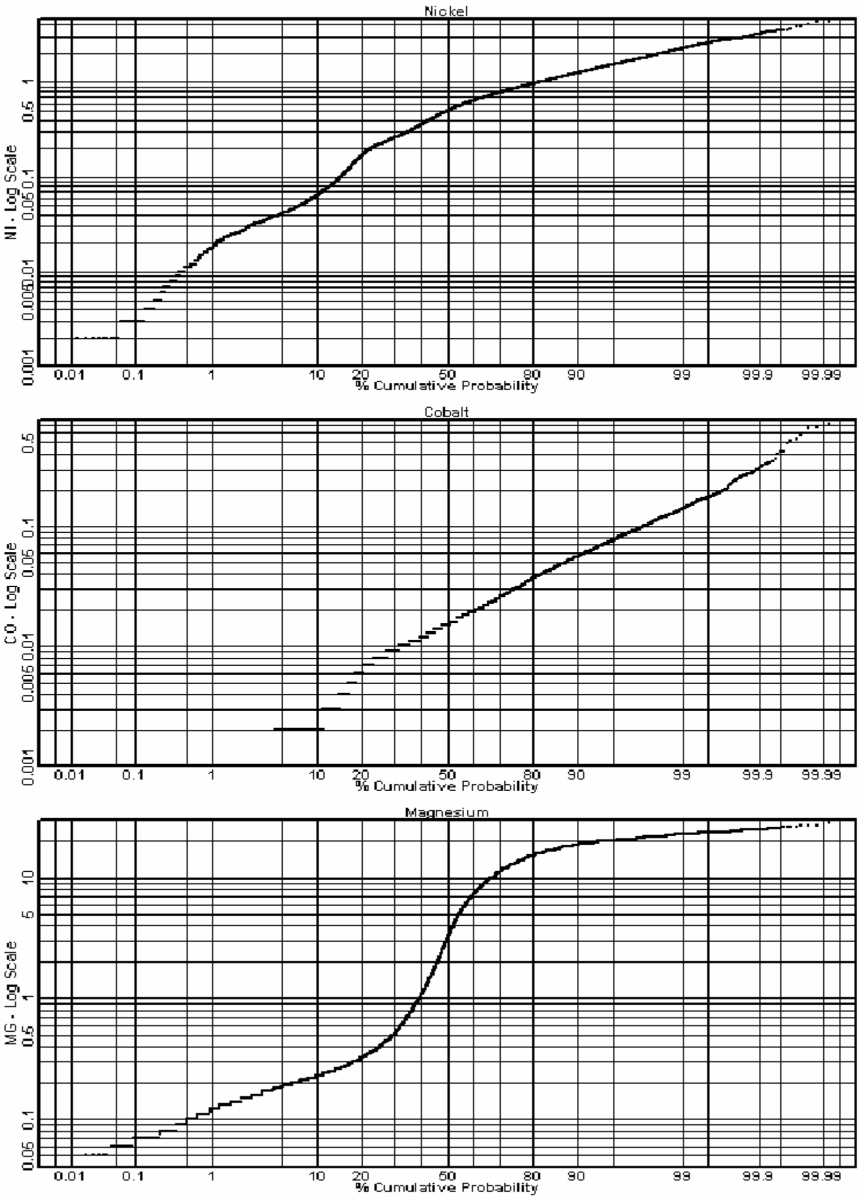
- The top of nickel enrichment, as defined by a sharp increase in nickel grades above a nominal 0.3 % nickel cut-off.
- The Co-Ni-Mn redox zone,
- The base of nickel enrichment, as defined by a sharp decrease in nickel grades to background levels below a nominal 0.3 % nickel cut-off.
- The magnesium discontinuity.

These boundaries were interpreted using the drillhole assay data supported by the geological logging. Although other elements are also either enriched or leached within the weathering profile they generally display enrichment or depletion characteristics largely consistent with the five zones defined above. The boundaries were wireframed and used to constrain statistical analysis, geostatistical analysis and resource estimation.

The effectiveness of these boundaries in subdividing the data into homogeneous geological domains can be seen in the distributions of the subdivided data. Figure 1 shows log-probability plots of the 2m drill hole samples. The plots show the separation of distinct enriched and unenriched nickel populations. Small proportions of enriched material assigned to the interpreted footwall are interpreted to be due to narrow, structurally controlled zones of deeper weathering. Conversely, the small proportions of unenriched material assigned to the enrichment zone are interpreted to be due to isolated ‘core stones’ of unenriched rock preserved within the ferralite zone.

The interpreted magnesium discontinuity divides the data into an upper low grade zone and a lower high grade zone within the saprolite. These zones are important for the control of the magnesium grades in the resource estimate. Mixed populations are still evident in the log-probability plots (Figure 2). This is due to a combination of the locally gradational nature of the magnesium discontinuity and the presence of “corestones” of saprolitic material within the ferralite zone.

Figure 1 Global log-probability plots for 2m composites



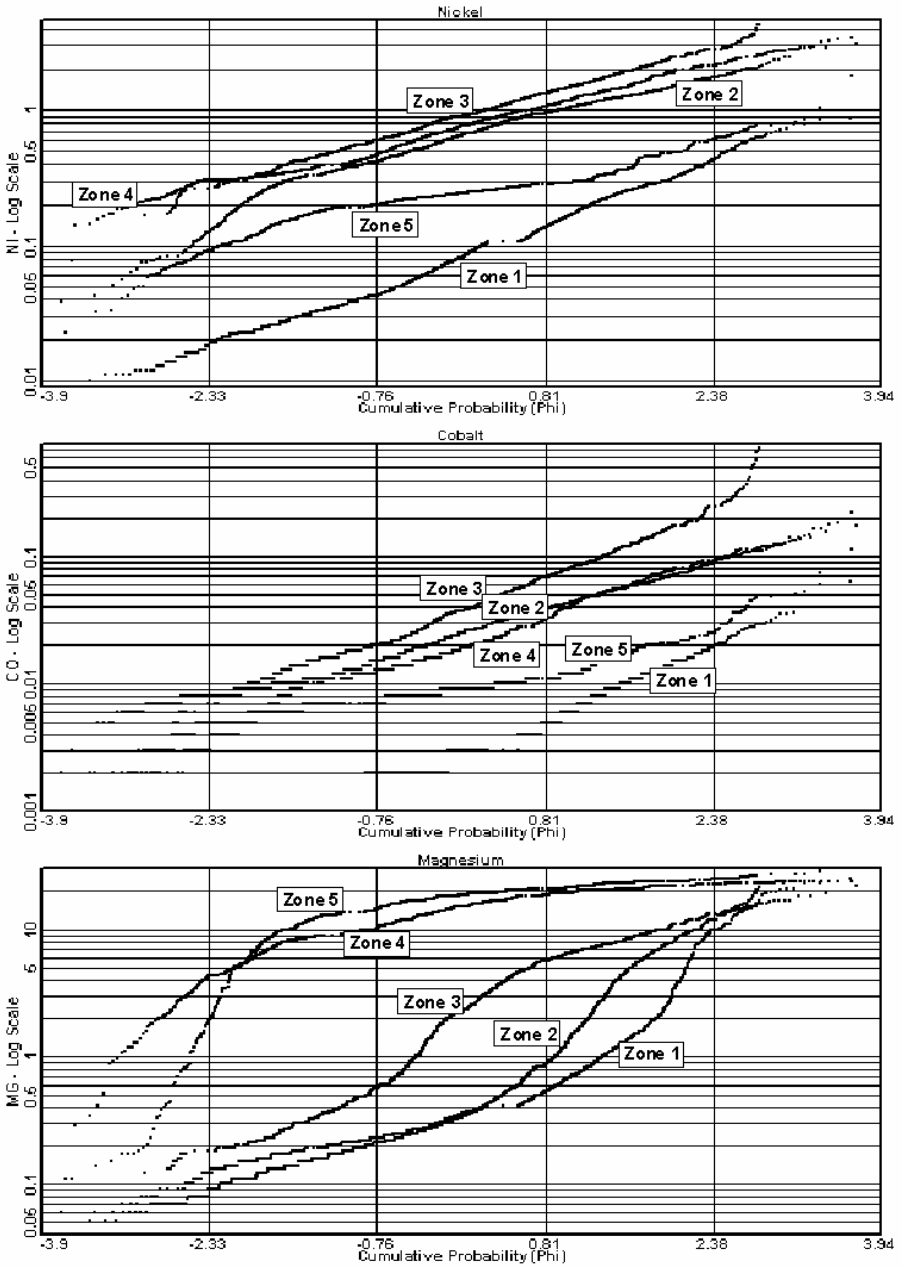


Figure 2 Log-probability plots subdivided by zone

Multiple Indicator Kriging (MIK) was initially selected as the preferred method of resource estimation since:

- It is less prone to over-smoothing of grades and conditional bias than Ordinary Kriging (OK) and other linear interpolation methods,

- It allows direct estimation of recoverable resources inclusive of dilution and ore loss.

- It is non-parametric and does not depend on prior assumptions about the shape of the distributions, unlike parametric methods, such as Multigaussian Kriging and Disjunctive Kriging.

Ideally, for economic evaluation of the deposit, all the elements of interest should be evaluated simultaneously. That is, the nickel, cobalt and magnesium grades of a given portion of the deposit at a given cut-off grade should be assessable. For methods that produce whole block estimates, this ideal presents no problem but for MIK some difficulties arise. MIK is a probabilistic method that defines the distribution of the grades of samples within each search window, providing a discrete approximation to the Conditional Cumulative Distribution Function (CCDF) for each block. When considering multiple variables the spatial relationships between the variables must be retained in the representations of the individual CCDFs. That is, the model should provide estimates of each variable for the same portion of the CCDF.

For MIK interpolation, the local CCDFs are usually based on one variable, for which multiple indicator parameters are modelled. Multiple Indicator Co-kriging systems require the co-regionalisation of the two variables to be modelled. However, such an approach only has a significant advantage if one of the variables is undersampled relative to the other. A further practical consideration is the additional calculation and modelling of indicator cross-variograms that are required with co-kriging methods.

An alternative approach to co-kriging is to establish one variable as the ‘mother variable’ and carry the grades of other variables with it. The mother variable and its search and interpolation parameters control the estimation of the other variable(s). In this way, the CCDFs of the other variables are based on exactly the same statistical and spatial support as the mother variable. For this to be a valid approach the variables must be spatially correlated and have similar patterns of continuity.

In order to determine whether MIK could be applied in this way to the multi-element resource model for the Halley’s deposit, it was necessary to examine the spatial relationships between the elements. This was carried out through simple statistical and geostatistical analysis of the drill hole data.

Bivariate statistical analysis of the data

The relationships observed between nickel, cobalt and magnesium were confirmed by generating scatter plots and correlation coefficients. These showed:

- Moderate to strong positive correlation between nickel and cobalt, particularly at the Co-Ni-Mn redox front,
- No apparent statistical correlation between magnesium and nickel.

The statistical relationship between nickel and cobalt indicated that simultaneous MIK modelling of nickel and cobalt grades might be appropriate but the case for magnesium was less clear. In geological terms there is an overall negative correlation between nickel and magnesium due to the leaching of magnesium and residual accumulation of nickel in the weathered profile. Superimposed on this trend is the accumulation of higher grade nickel mineralisation near the Co–Ni–Mn redox and near the magnesium discontinuity, which is a steep geochemical gradient rather than a homogeneous domain. The distribution of magnesium grades in the nickel enrichment zone is also strongly bimodal. For these reasons it was difficult to establish any statistical correlations between magnesium and nickel.

Variography

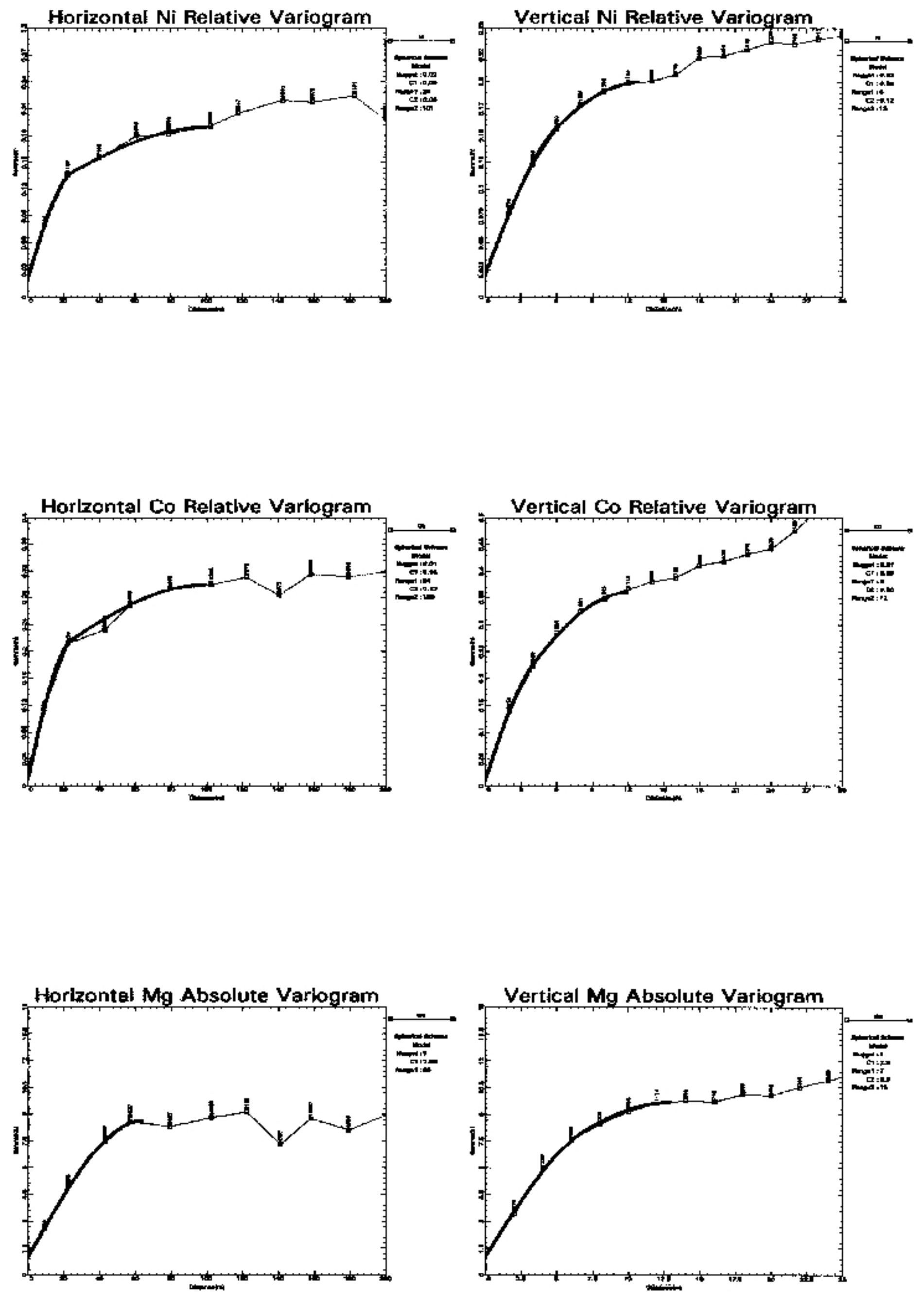
Directional variography was carried out using grades and indicators. Since the nickel enriched material forms a gently undulating zone and the zone is not constrained by internal grade boundaries, unfolding techniques were used to honour the continuity of mineralisation. The digitised Co–Ni–Mn redox surface was used to unfold samples within the ferralite zone and ensure that high grade nickel and cobalt intercepts were correctly correlated from hole to hole. Beneath the magnesium discontinuity the nickel, cobalt and magnesium data were unfolded to the magnesium discontinuity. Ferralite and saprolite data were examined separately. When unfolding techniques are used, the inferences of dip orientations are not relevant, as the variogram calculations are restricted to the two-dimensional plane of the unfolding surface.

All the grade variograms were well structured. The variograms showed some regional anisotropy but for practical grade estimation purposes were largely isotropic in the plane of the unfolding. Ranges from 65m to 130m were observed and modelled. Down hole variograms provided clear structures with low nugget variance and modelled ranges of 10m to 13m in the minor axis direction.

The variograms for nickel and cobalt were very similar and displayed structures with ranges of about 20m and 100m, as illustrated in Figure 3. The variograms for magnesium showed a single structure with a range of about 60m. Interestingly, the magnesium variograms changed little when the data were unfolded to the Co–Ni–Mn redox rather than the magnesium discontinuity.

For the Halley’s resource model the objective was to build local CCDFs based on nickel and determine the grades of elements associated with nickel, above various nickel cut-off grades. In MIK modelling, the grade variogram parameters are not used directly in the interpolation process. Since nickel is the variable of greatest importance and elements such as cobalt and magnesium have similar anisotropies it was initially decided to use nickel as the ‘mother’ variable and carry the grades of the other elements with it during MIK. Using this approach, only the indicator variograms for nickel were required.

Figure 3 Unfolded variogram models for the ferralite zone



The cumulative log-probability plots of nickel grades were used to establish cut-off grades at regularly spaced percentiles across the distribution. Directional variograms were generated at each cut-off using the same lags and tolerances as were used for the grade variography. All the nickel indicator variograms were well structured and displayed continuity similar to the grade variograms. The indicator variograms for the ferralite zone had lower nugget variance and slightly longer ranges that those from the saprolite zone, indicating that continuity of nickel mineralisation is better in the ferralite zone.

Grade estimation

Multiple Indicator Kriging (MIK) works on a probabilistic basis to define the distribution of the grades of samples within each search window, providing a discrete approximation to the CCDF for each block. As this distribution is based on the samples found within the search window centred on any given point, it changes from block to block to reflect local grade variability.

Several cut-off classes were selected for each model block, so that an equal number of samples occurred in each class. The cut-off classes varied from block to block to reflect the local variability of the samples within the search volume. For example, in a low grade area, the cut-offs were generally low, but for blocks in a high grade area, higher cut-offs were selected. This provided a better approximation of the CCDF of the local samples than could be achieved with a fixed set of cut-offs for the whole data set. Whilst this is ideal for modelling the distribution of grades within the deposit, it is impractical for the purposes of reporting the resource or mine planning. Therefore, after the CCDFs were estimated at each block centroid, the model was further processed to provide probabilities and grades within blocks, for a range of fixed cut-offs that covered the range of potential mining cut-off grades.

Each of the spatial domains defined by the geological interpretation were interpolated separately. The samples in each domain were unfolded to the relevant unfolding surface in that domain.

The MIK method allows resource estimates to be reported in several ways, including:

- the average block grade, (E type estimate); or
- the recovered tonnes and grade (MIK estimate) defined by a selective mining unit (SMU).

The E-type estimate is simply the average grade of the block derived by weighting the grade in each cut-off class by the probability for that class. When assessing the resource in terms of the E-type estimates, it is assumed that the entire block has a single grade and that selective mining is not possible. Once a cut-off grade is applied, the E-type estimate therefore incorporates high dilution and high ore loss.

The CCDF distribution at a block centroid initially reflects the variance of the grades of the samples within the search window. When estimating recoverable resources we are more interested in the variance of grades based on SMU support, as opposed to sample support. The SMU block size represents the smallest practically mineable volume that can be extracted, given the still imperfect resolution of sampling at the grade control stage. The variance of the SMU grades will be smaller than the variance of the samples. In order to convert the prior CCDFs based on sample support to posterior CCDFs reflecting SMU support, a variance correction is required.

The volume-variance relationship, or Krige's relationship, states that the variance of samples within a domain of interest is equal to the variance of samples within SMU sized blocks plus the variance of SMU sized blocks within the domain of interest. This relationship allows local recoveries based on SMU support to be estimated.

There are several possible approaches to change of support variance correction including the affine correction and indirect lognormal correction. For the Halley's deposit, an indirect lognormal correction of variance was used. This is a method that borrows the transformation that would have been used if the original sample support distribution and the transformed block support distribution were lognormal. The idea behind it is that while skewed distributions may differ in important respects from a true lognormal distribution, change of support may affect them in a manner similar to that described by two lognormal distributions with the same mean but different variances (Isaacs and Srivastava, 1989). The correction operates by 'squashing' the CCDF at each centroid. The mean of the distribution is maintained but the variance is reduced. The indirect lognormal correction results in some reduction of skewness. For example, for positively skewed data, the tail of very high values is squashed in towards the mean grade more than are the low grade values. Although the mean of the CCDF will be unchanged, the mean grade above a cut-off grade will change.

The change of support correction factors can be derived theoretically using the grade variogram models. However, the grade variograms derived in this particular study were of such large range and low nugget variance that the correction factors estimated from the models, assuming an SMU size of about 5m by 5m by 2m, would result in minimal change of support. In practice, factors such as undulations in the enrichment zone, movement during blasting and irregularities in bench floors mean that 'theoretical' selectivity will not be achieved. The variance correction used for the Halley's resource model was adjusted to reflect these practical conditions.

Conditional Simulation

Kriging, in common with other grade interpolation methods, results in smoothing of the true dispersion (the variability) of the grade. This leads to overestimation of low grades and underestimation of high grades. The probabilistic estimates produced by

MIK methods often reduce this effect but the local grade variability may still be incorrectly characterised. This failure may result in incorrect estimation of recoverable resources. Since recoverable resource estimates were the aim of the modelling for Halley's deposit, the MIK results were validated using conditional simulation.

Conditional simulation is a series of methods for producing models on a detailed scale to simulate the spatial and statistical characteristics of a deposit. The simulations are conditioned to the known data points and honour the spatial continuity as modelled by the variogram, but are not smoothed. They therefore preserve the local variability of the deposit.

A sequential Gaussian technique was used for the Halley's deposit. In simple terms, a typical sequential Gaussian conditional simulation involves:

- transforming the data values to a normal distribution using a Gaussian transform function;
- creating a dense grid of points, or nodes, for which the grades will be simulated;
- selecting a node at random and allocating a value at random to that node, conditioned to the conditional moments (simple kriging mean and variance) defined at each location from the real data points;
- repeating the process by selecting further nodes at random but now using the values at previously simulated nodes as well as the real data, until all nodes are simulated; and
- finally, back-transforming the simulated Gaussian values.

Each simulation run produces an image or realisation of the deposit that correctly reflects the statistical and spatial variability of the real data. The true data values are retained wherever they correspond with a node. Multiple realisations are required to enable the impact of local variability to be assessed. Collectively these realisations are referred to as the conditional simulation model.

Two trial areas were drilled in the Halley's deposit, one towards the eastern margin of the ultramafic unit where the magnesium discontinuity was gradational and a second area in the middle of the deposit where the discontinuity appeared to be much sharper. Holes were drilled at 10m spacings along a series of intersecting lines, running parallel, orthogonal and diagonal to the regular drilling grid. The pattern was chosen to provide detailed coverage in several directions (azimuths), whilst minimising the total amount of drilling. The holes in the detailed drilling pattern were sampled on 1 m intervals.

The original and close spaced drilling data were used to generate a conditional simulation model comprising 50 realisations that reflect the spatial and statistical variability of the data. Three variables were simulated:

- the nickel grade in the ferralite zone and saprolite zone;
- the elevation of the magnesium discontinuity;
- the magnesium grade in the ferralite zone and saprolite zone.

In the case of the grade variables, the 2m composite assays from both the regional RC drilling (40m by 50m grid) and the close spaced RC drilling (10m by 10m grid) were used as the conditioning data. For the elevation of the magnesium discontinuity, the data points on the digitised surface were used for conditioning.

A mixed simulation model using nodes on a 1m by 1m by 2m grid was then developed for each realisation as follows:

- all the nickel grades were used from both the ferralite zone and the saprolite zone without constraint;
- the elevation of the magnesium discontinuity was applied to the simulation to define the ferralite and saprolite zones;
- magnesium grades from the ferralite zone and saprolite zone were modelled independently.

For the purpose of comparison of volumes and grades of the simulation model with the recoverable resource model, the simulation model was regularised to a cell size of 5m by 5m by 4m, the nominal size of the SMU.

In addition, three other MIK resource models were generated for the trial area to examine the effects of using additional drilling on the interpretation of the magnesium discontinuity and on the grade estimation. These models used various combinations of regular and detailed drilling data and they were compared to the best case, worst case and "most likely result" conditional simulation models. The "most likely result" was defined as the probability weighted mean grade above a nominated cut-off for all 50 cases. From these comparisons it was apparent that:

- the MIK model was producing good estimates of the volume and grade of nickel mineralisation above various cut-off grades;
- the variability of the elevation of the magnesium discontinuity was high, and accordingly difficult to predict locally;

- the variability of the magnesium discontinuity significantly affected the average magnesium grades

- within individual domains, the MIK estimates for magnesium were lower than the simulated grades.

Since the magnesium content of the ore is directly related to ore processing costs it was considered undesirable to run the risk of underestimating magnesium grades in the resource model. In order to reduce this risk a revised, more conservative approach to modelling the magnesium grades was taken. The simulation indicated that the interpreted elevation of the discontinuity tended to be too low, so the interpreted discontinuity was raised by 2m to create a new constraining surface. Samples were flagged according to the original interpretation but then interpolated into ferralite and saprolite domains defined by the revised surface.

The simulation models suggested that the MIK estimates based on a nickel mother variable were underestimating magnesium grade. This was probably due to the weakness of the correlation between magnesium and nickel grades and showed that the initial conclusion that magnesium grades could be carried with the nickel grades was invalid. For the revised model, magnesium grades were interpolated using ordinary kriging. The revised modelling resulted in a local increase in magnesium grades immediately above the magnesium discontinuity, a small increase in the magnesium grade of the resource overall, and a much better correlation with the simulations.

Mine Planning

The MIK, E-type and OK resource estimates for the Halley's deposit are quite similar (Table 2) even at higher cut-off grades.

Table 2.. Comparison of resource estimates at a 0.5% and 1.0% nickel cut-off grades

	Cut-off	0.5% Ni			1.0% Ni	
Estimate	Mtonnes	Ni (%)	Co(%)	Mtonnes	Ni (%)	Co (%)
OK	63.2	0.87	0.04	16.6	1.25	0.05
E-type	64.7	0.86	0.04	15.6	1.25	0.05
MIK	59.4	0.90	0.04	16.9	1.31	0.05

This reflects the good continuity of the nickel grades and effective unfolding of the data during grade estimation. Larger variations would be expected in deposits where short scale variability of grades is higher and in these deposits evaluation of the recoverable portion of the resource becomes more crucial.

Whole block estimates are much simpler to work with for mine planning. Not only are they computationally much less onerous, but they also avoid the difficulties of combining probabilistic estimates of variables such as nickel and cobalt with smoothed, whole block estimates of other variables such as magnesium and bulk density.

Importantly, whole block estimates are also much easier to present to parties such as engineers and financiers, who may have no familiarity with geological or geostatistical concepts or who may only be familiar with more empirical approaches to modelling ore loss and dilution. At the feasibility study and financing stages of a project these may be relevant considerations.

For the mining studies that form the core of the reserve estimation and mine planning for the Ravensthorpe Nickel Project the E-type estimates for nickel and cobalt were used in preference to the MIK estimates. Mine planning was therefore based on marginally lower nickel grades than are expected to be achieved by selective mining. The weak negative correlation between nickel and magnesium indicates that selective mining by nickel cut-off grades may also achieve slightly lower magnesium grades. The E-type and OK estimates provided simple robust means of designing and scheduling the mine and the MIK estimates can be used to test the sensitivity of project cash flow to the better recoveries anticipated from selective mining.

Conclusion

The studies completed for the Ravensthorpe Nickel Project provide an illustration of some of the difficulties that emerge when estimating recoverable resources for nickel laterite deposits. The challenge is to provide estimates for several variables that honour the statistical and spatial characteristics of the individual variables but also honour the spatial relationships between those variables. Multiple Indicator Kriging with nickel as the mother variable carrying cobalt was shown to be a viable approach to the estimation of recoverable nickel and cobalt resources in the Halley's deposit. In deposits where cobalt is of sufficient economic importance to warrant inclusion in cut-off grade criteria, further adaptation of this method by use of equivalent grades may be necessary.

This case history also highlights the value of conditional simulation as a tool for validating both grade estimates and the position of grade boundaries within the deposit. As well as detecting a deficiency in the original estimates of magnesium grade the conditional simulation also provided a view of short range variability in the deposit and an additional guide to resource classification.

For mine planning purposes, the choice between MIK estimates for multiple variables rather than E-type or OK estimates depends on the sensitivity of the project to selective mining estimates and the practicalities of handling and presenting data for multiple CCDFs. For the Halley's deposit, the strong continuity of grades resulted in relatively small differences between the MIK and E-type estimates so a combination of E-type and OK estimates was adequate for most mine planning purposes. For projects in which variability is greater and a higher degree of selectivity is required during mining, more complex, computationally intense approaches are required to evaluate multi-element MIK models.

Acknowledgements

The authors would like to thank Comet Resources NL for permission to publish this paper.

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