IMPROVING PREDICTIONS BY STUDYING REALITY

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ABSTRACT

Case studies involving a range of approaches to modelling a variety of orebodies highlight the importance of geological controls and constraints as well as understanding statistics and geostatistics in achieving predictions which reconcile with reality.

Reconciliation issues can be related to mineralisation style and the failure to recognise the appropriate boundary and statistical/geostatistical characteristics. In zonal orebodies such as stockworks the head grades are often lower than predicted and tonnage higher than predicted. The effective cutoff is higher than designed and there is more metal on the low grade stockpile than expected. The resource model is too selective compared with mining reality. On the other hand structured orebodies may have higher head grades than predicted and lower tonnages due to sampling issues such as smearing of grade in reverse circulation percussion drillholes.

A number of case studies are used to illustrate the effects of various modelling approaches on ore reserve reconciliation. These include the use of grade control kriging to calibrate the resource model, re-handling of marginal material by truck sampling showing the regression effect between assays and mining units, the effect of using boundaries with or without geological matching depending on mineralisation style and auditing techniques to isolate problem areas prior to production.

Predicting ore reserves without due regard for physical grade characteristics is dangerous, regardless of interpolation technique. An understanding of the geology, mineralisation continuity, boundary style, selective mining unit variability and the grade/cutoff enigma can go far towards assisting in the calculation of recoverable reserves and in reconciling various estimates with actual production.

Mining is a risky business; resources and reserves are estimates, not hard facts. We need to improve our predictions, and geostatistics for the next century will have to draw on realities from the rich tapestry of mining experiences world-wide in order to provide the tools of the future.

INTRODUCTION

As a practitioner in the field of resource estimation I have been fortunate enough to be involved in the Australian mining industry during a 6 year period of intensive growth and learning. This period has been a very active time for gold as well as base metals, iron ore and other commodities. The nature of the industry in Australia is such that the lead time from discovery to exploitation and reconciliation can be as short as a couple of years. This gives us ample opportunity to learn about the practicalities of prediction and to establish track records. The concern for the consultant is that we are readily accountable for our estimates. The Australian ethos is such that instant praise or criticism is reaped depending on perceived performance appraisal. These perceptions may be fair or unfair and may be biased depending on whether the client is a buyer or seller, operator, banker or competitor.

The consultant must of course be impervious to perceptions and must concentrate on getting the correct estimate. This usually means accurately predicting the tonnes and grade that can be delivered to the plant for a given mining method, mining rate, selective mining unit and cutoff grade. It is not good enough to predict the in-situ resource without regard to mining parameters. What is of importance to a producing mine is having a budget and mining schedule which is achievable.

Ore reserves are of course dynamic. Most Australian operations review their ore reserves on an annual basis at least. This gives them the opportunity of building into their future predictions the knowledge gained from mining to date. The importance of close analysis of grade control spaced drilling is becoming more and more evident as increasingly more mines find that they can fine tune their mining selectivity criteria such as setting cutoff grades on selective mining units rather than sample grade.

As a group, originally only myself but now 10 professionals, four of whom are involved in resource estimation, we have examined data from nearly 400 operations in the last 6 years. Many of these have been mined out now and we have been able to do post mortem analyses on a significant number of open pits as well as a few underground operations. We can thus offer some observations on the do’s, don’ts, may-be’s and would-like-to- have’s in the industry today. There are some patterns emerging and, although some of these may be unique to the Australian scene, it is likely that they may also be of international interest. It is hoped that the empirical results offered will be of assistance to the researchers to whom we look for new geostatistical methods and procedures in the next century.

It is well established that when the operation is on budget and achieving satisfactorily then management questions nothing. However, as soon as there is a problem, outside advice is sought. So it happens that we are most often called in to review a problematic situation and there have been a kaleidoscope of interesting situations reported to us. Some that come to mind include:

- Head grade lower and tonnage higher than predicted
- Head grade higher and tonnage lower than predicted
- Both tonnes and grade lower/higher than predicted
- Low grade stockpiles/truck samples higher grade than predicted
- Operation reconciles pit to production at one cutoff then fails to reconcile when cutoff is raised
- Production cutoff must be raised to match estimated production at the same cutoff

Most geostasticians will recognise that these problems boil down to a few significant theoretical explanations revolving around distribution statistics and the volume-variance relationship and the failure of the mining industry professional to take these into account when calculating ore reserves and during delineation o grade control blocks.

Thus polygonal and sectional reserve estimations and polygonal grade control can answer for many of the perplexing situations. However, a significant proportion of the problems are related to mis-use of geostatistics as well. Some that come to mind include:

- Incorrect boundary recognition
    - Structured vs zonal
    - Mixing geological populations
- Incorrect interpolation technique
    - Skewness
    - Range of influence
    - Anisotropy
    - Nugget Effect
- Unsuitable definition of selective mining unit
    - Recovery function
    - Block size
- Inability to define semivariograms
    - Using too-tight boundary conditions
- Computational errors

The most fundamental of all errors is that of sample bias. Inappropriate or inadequate sample collection, crushing, splitting and analysis techniques give rise to non-representative assays. It is very necessary to correct sampling problems before statistical and interpolation errors combine with sampling errors to give inordinate uncertainty.

Each combination of issues can lead to a different problem, some of which have become evident during recent reviews we have undertaken. Case studies involving a range of approaches to modelling a variety of orebodies highlight the importance of geological controls and constraints, in particular the recognition of boundary style as it impacts on compositing and interpolation technique. Statistics and geostatistics do not solve physical or sampling problems and do not replace geological interpretation. Within appropriate geological constraints they are the tools which will quantify risk, confirm spatial continuity and compensate for the volume-variance relationship between assay sized volumes and selective mining units.

Reconciliation issues can often be related to mineralisation style and the failure to recognise boundary and statistical characteristics. In zonal orebodies head grades are often lower than predicted and tonnages higher than predicted. The effective cutoff is higher than designed and there is more metal on the low grade stockpile than expected. The resource model is too selective because of insufficient smoothing.

In structured orebodies the head grade is commonly higher than predicted and tonnage is lower. There is too much smoothing, possibly due to smearing of grade in RC holes.

The third common problem area is in supergene (oxidised and remobilised) zones where production gives more metal than expected. The cause of this is insufficient sample mass for coarse gold with a high nugget effect.

Predicting ore reserves without due regard for physical and grade characteristics is dangerous, regardless of interpolation technique.

MACRAES MINE

The Macraes Gold Mine in Otago, New Zealand, is used as a case study illustrating a complex intermixture of structured and zonal environments to show the effects of various modelling approaches on ore reserve reconciliation. The project derived significant benefit from recognising how to apply the effective production cutoff to selective mining units rather than to raw blast hole assays. Grade control kriging was used to calibrate the resource model (Figure 1). It also helped in understanding the regression effect intrinsic in the results of re-handle truck sampling of low grade material which was consistently higher in grade than the blast hole assay averages. Re-handle sampling was subsequently discontinued and the cutoff was applied to smoothed selective mining unit grades. This resulted in significantly improved reconciliation between in-pit estimates and plant head grades, at the same time yielding an increase in total gold production.

After more than a year's mining, grade bias become a problem during grade control sampling at Macraes (Figure 2). Pit to mill reconciliation, which had previously been good, gradually began to deviate. The bias was tracked to the loss of low grade fines from the cyclone of the grade control drilling rig. Once the rig was replaced the bias was removed and good reconciliation was restored.

TEMORA MINE

Both the long term and low grade stockpiles at Temora Gold Mine in New South Wales, Australia, were historically understated by virtue of the combined effects of analytical laboratory inaccuracies, mining practices and orebody characteristics.

Over five years of milling it is reported that the laboratory (or sampling methods) understate gold production by 3 to 4% in terms of the assayed mill feed grade. This affects the metal balance but does not explain the difference between the stockpile assigned grade and the mill feed grade.

Grade control blocks are marked out using an assay cutoff:

Waste	0-0.3 g/t
Marginal	0.3 – 0.75 g/t
Low grade	0.75 – 1.5 g/t
Long term stockpile	1.5 – 2.8 g/t
High grade	>2.8 g/t

The average grade assigned to blocks has consistently been, not an arithmetic average, but the geometric mean or median of the blast hole assays. As the assay population is skew (close to lognormal) the median is consistently lower than the true mean grade (Sichel Mean), resulting in a consistent understatement of grade.

The correct use of the mean rather than the median in averaging is shown to have the effect of increasing grades as follows:

Waste	+50%
Marginal	+15%
Low Grade	+9%
Long Term	+12%

The result of the positive analytical sample bias and the statistical effect of using the geometric mean when estimating block grade both contribute to an understatement of grade. Vertical grade control drilling is not likely to inform the small scale vertical high grade structures adequately, also contributing to a grade bias. The use of high cutoff grades is likely to lead to an additional bias caused by the volume variance effect which gives rise to a regression between true block grade and blast hole assay grade. This leads to overestimation of high grade blocks and underestimation of low grade blocks.

These observations all led to conclusion that the stockpile grades at Temora had a high probability of being better than original block grades would suggest. Predictions based on retrospective indicator kriging of grade control data were confirmed by subsequent processing of the low grade stockpile.

COPPERHEAD MINE

The combination of complex geology, skew assay distributions and polygonal methods of grade control at Copperhead Gold Mine, Western Australia, resulted in significant low grade gold stockpiles at higher grades than expected. After four years of mining a review was undertaken to assess the remaining reserves including stockpiles.

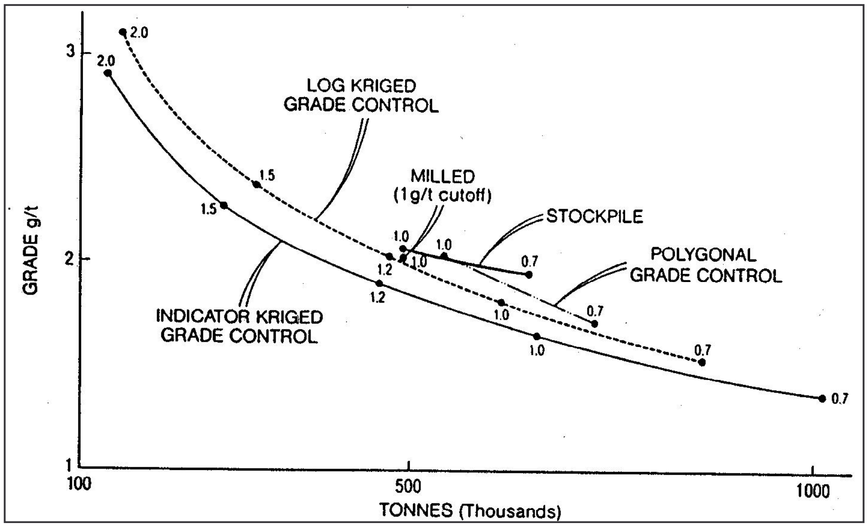

Figure 1 Grade/Tonnage Reconciliation Diagram at Macraes

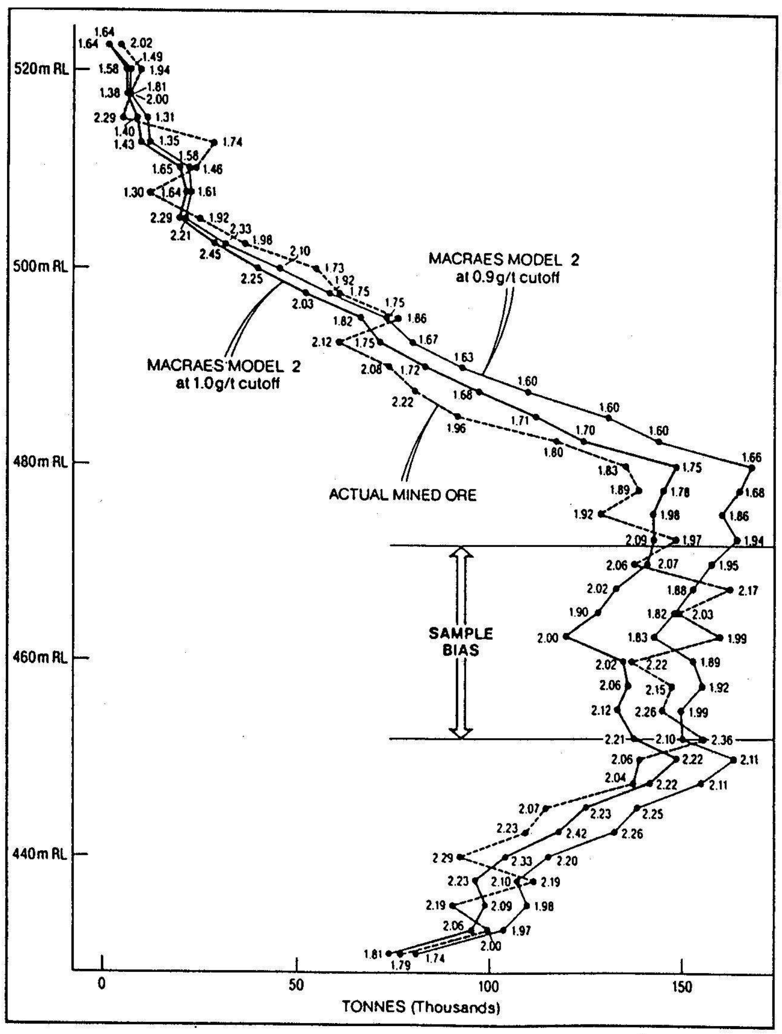

Figure 2 Grade Trend Showing Sampling Bias at Macraes

West plunging stratabound mineralisation of folded mafics of a northern series and stratabound mineralisation of banded iron of a southern series are both modified by west dipping cross fractures and shear zones which enhance mineralisation. For the review, domain boundaries were digitised on previously mined benches then extended down plunge below the current pit base. Stoping and development levels underground were used to assist in making the interpretation.

Lognormal kriging was chosen because the data is perfectly lognormally distributed. All available assays were used in kriging each domain but using the specific parameters for a given domain. This was designed to avoid edge effects at the domain boundaries since these are gradational and were not interpreted with any degree of exactness.

Exploration and grade control kriged results were compared with production estimates based on polygonal grade control block outlines to determine the effective SMU cutoff grade being achieved using a given blasthole assay cutoff. The exploration model was reconciled with the grade control kriging in the mined-out area to give confidence in the remaining reserves.

Reconciliation results were as follows:

Production	568,000 tonnes at 2.6 g/t >= 1 g/t assay cutoff
Exploration	544,000 tonnes at 2.9 g/t >= 1.4 g/t block
	589,000 tonnes at 2.7 g/t >= 1.3 g/t block
	638,000 tonnes at 2.6 g/t >= 1.2 g/t block
Grade Control	553,000 tonnes at 2.7 g/t >= 1.2 g/t block

Reconciliation with production estimates suggests the bulk kriged model is a good predictor of average tonnes and grade.

The effective production cutoff grade on SMU's of 5x5m on a 2.5m bench is 1.2 g/t compared with an assay cutoff of 1 g/t on blastholes. This is likely to be the major reason for material stockpiled below the assay cutoff of 1 g/t (block cutoff 1.2 g/t) returning grades higher than estimated and explains the higher than expected stockpile grades.

Detailed reconciliation showed that the model underestimated tonnes and grade where drilling was limited and at depth due to an apparent low grade bias in the RC drilling. Management were alerted to drill target holes to validate the results of the earlier deep drilling program. The model overestimated in domains known to suffer a high grade sampling bias. Thus although on average the model performs well, in detail there are various imperfections, none of which could be overcome by modelling technique alone.

BODDINGTON GOLD MINE

Pit A at Boddington Gold (BGM) in Western Australia has the following laterite profile layers which were used to create a solid model of geological features:

Feature
Base of gravel
Base of hardcap
Base of B Zone
Base of clay

Hardcap and B Zone assays approximate lognormality. Gravel and clay both represent mixed populations as would be expected considering their physical and grade characteristics. As the high grade sub-populations may have different structural characteristics from the lower grade population, indicator semivariograms and indicator kriging were necessary to model the clay and gravel and were used for hardcap and B Zone as well.

The method of nested median indicators using 10 indicators was used. The uppermost grade category for each zone was based on a top cut close to the median grade of that category. Comparison with lognormal kriging was also undertaken.

Anisotropy was established by logarithmic semivariograms and indicator semivariograms were then calculated for each of the indicator cutoffs along the main structural directions.

Indicator variography was based on absolute semivariograms run on the 1's and 0's for each variable (ignoring the values below the previous cutoff). Nested indicator kriging is based on ordinary kriging of the 1's and 0's for each indicator in turn using the appropriate semivariogram for that cutoff.

After the sixth or seventh indicator there is either insufficient data or the semivariograms exhibit pure nugget effect. Kriging for the subsequent cutoffs uses the last meaningful semivariogram calculated. Logarithmic semivariograms display ranges and nugget/variance ratios similar to the first (median) indicator.

The relationships between the ranges of influence and indicator cutoffs are illustrated in Figure 3. B Zone shows a slight drop in range of influence as cutoff increases. Hardcap shows a very marked linear drop in the long range structure as cutoff increases but a more constant small range structure. The range/cutoff relationship for clay is constant until the fourth indicator cutoff is reached with a subsequent rapid decline in the long range from 130m to 50m in spatial continuity. The detailed indicator variography reported here suggests that the range of influence does not necessarily have a simple linear relationship with cutoff but that this relationship is different for different domains and may show either a stepped decline as in B Zone or a sharp drop as in hardcap. The clay zone demonstrates a combination of two rates of decline above and below the fourth indicator.

The block model was interpolated using nested indicator kriging employing 10 ordinary kriging runs on the zeros and ones corresponding to the 10 indicators for each of the three zones separately. The recovery above cutoff was corrected to the minimum selective mining unit. Lognormal kriging was separately undertaken using KRIGE3 from the Geostat system. The kriging parameters were defined from logarithmic semivariograms after normalising the total sill to the logarithmic variance of the input grade composites for each zone. The lognormal shortcut was used to estimate the selective mining estimate.

A maximum of 25 composites was used to krige each block which was discretised into 3 x 3 x 2 subcells. A minimum of 5 composites were necessary to krige each block. For both models, a global weighted grade was calculated according to the proportion of each lithology in the blocks, the SG and the corresponding calculated grade.

The comparative estimates are all displayed on the grade/tonnage diagram in Figure 4. The selective indicator estimate $\geq$0.5 g/t reconciles closely with the in-pit estimate at the same cutoff. The log kriged results give higher grades at lower tonnages for a substantial increase in estimated metal content at all cutoffs compared with the indicator model. The reason for this is believed to be the pronounced bimodality evident in the clay horizon. This inflates the logarithmic variance which in turn inflates the kriged estimate. Certainly, in the case of the clay zone, it is expected that the indicator model will provide a more appropriate response than the log kriged model because of the distinct bimodality of the distribution.

GIRILAMBONE COPPER MINE

Girilambone mine is a new copper mine in New South Wales, Australia. This deposit was originally modelled using strict geological boundaries as well as assay boundaries to constrain ordinary kriging without a top cut. As soon as mining commenced it because evident that there was a good deal of material around 0.5%Cu which had not been interpolated in the model. A review of the block model showed that an artificial bimodality had been imposed on the model by virtue of the 1%Cu assay boundary used to constrain high grade blocks (Figure 5).

Relaxing the assay constraint and reinterpolation using indicator kriging changed the grade/tonnage curve significantly. The effect on the reserve above a 0.5% cutoff is to double the reserve tonnage. The grade hardly suffers because of the flat gradient of the grade/tonnage curve (Figure 6).

Production schedules for this mine had to be adjusted to reflect the increased bench ore tonnage and the life of mine has been extended. Tonnage sensitivity at low cutoffs means that grade control kriging is essential to overcome the regression effect which could potentially lead to misclassification of ore and waste. Because of the skewness of the data, grade control kriging, using Gemcom’s ORECONTROL system, needs a top cut applied prior to ordinary kriging. Geological boundaries are superimposed prior to blocking out of ore and waste.

CONCLUSIONS

There is no single approach to orebody modelling which can always be guaranteed of getting the answer right. The style of the mineralisation tends to dictate the modelling approach needed.

Experimentation with various interpolation techniques shows that where geological interpretation is simple and there are single statistical distributions, different methods can give similar results.

Even lognormal kriging, which is taboo to so many in the industry, and was once described to me by Michel David as “riding a wild horse”, can give remarkably accurate results if applied correctly to a well defined lognormally distributed assay population. Indeed it is more effective than other techniques in mapping cutoffs correctly as it is sensitive to the presence of low grade boundaries. However, lognormal kriging displays a reluctance to be bullish where input data is too wide spaced and does, of course, demand that the sill of the semivariogram accurately reflects the population variance.

Indicator kriging is a more universally applicable practical technique as it can cope with mixed distributions as well as simple distributions. Where indicator kriging shows most sensitivity is in the top grade category. Should assays in the top category be cut and if so to what level? We have demonstrated remarkable sensitivity to this top category and experience suggests that better reconciliation is likely with a top cut. We have, interestingly, also found that the single logarithmic semivariogram (which is similar to the median indicator semivariogram) can be used with nested indicator kriging without loss of sensitivity.

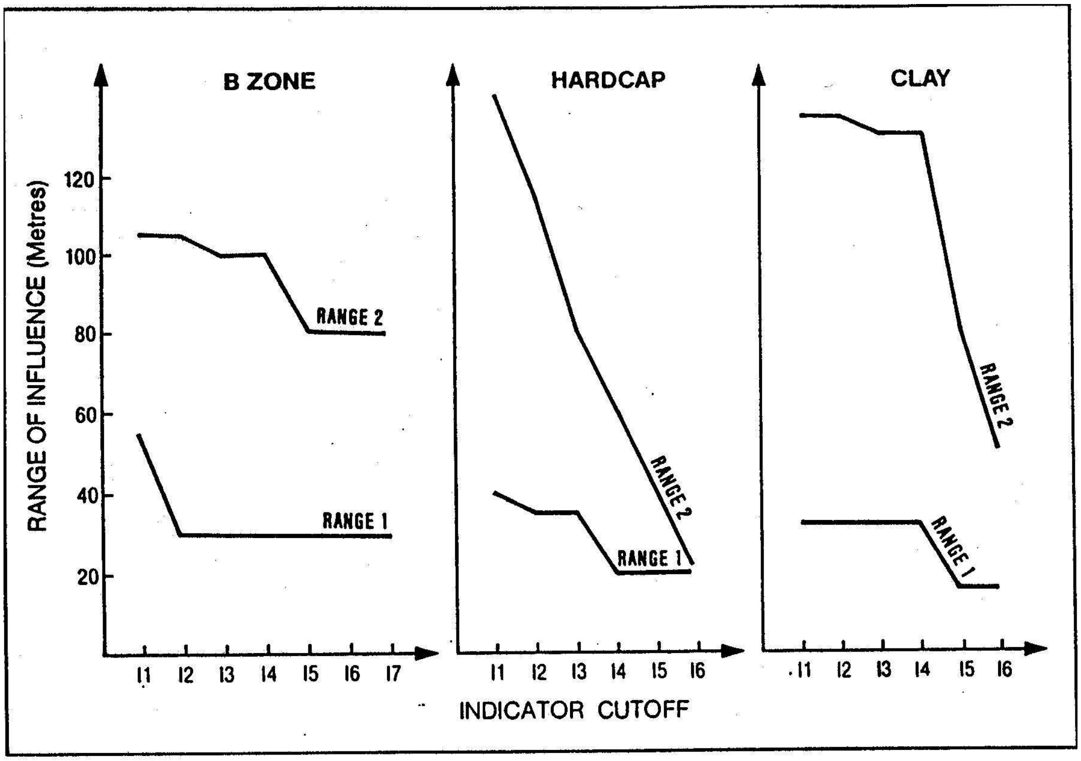

Figure 3 Relationships Between Ranges of Influence and Indicator Cutoffs

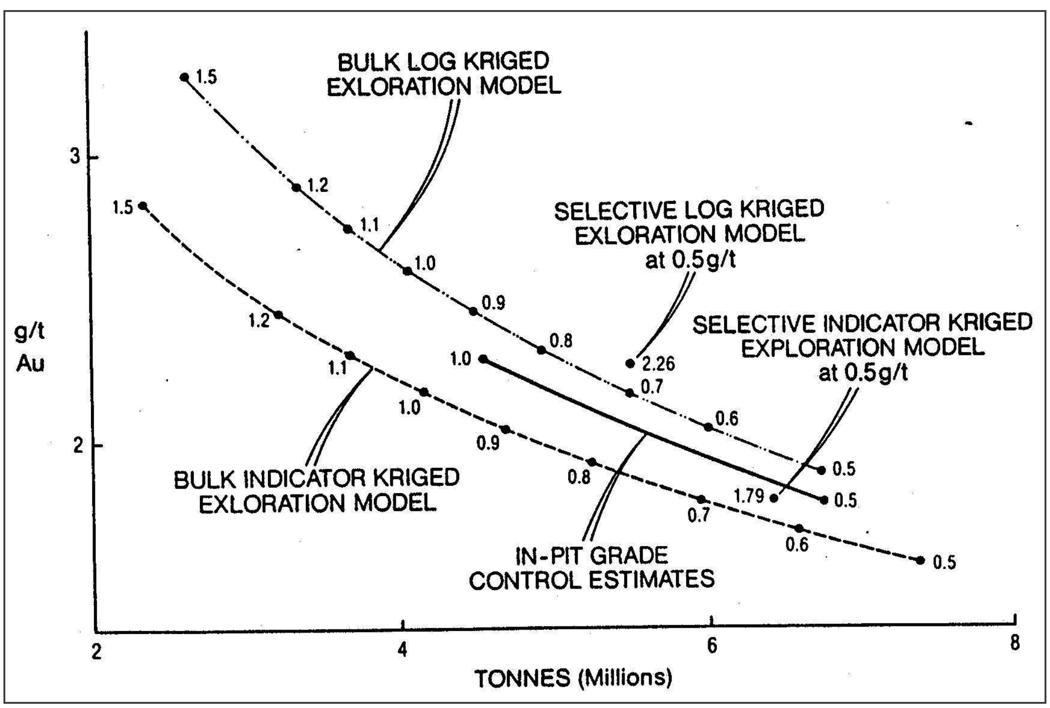

Figure 4 Comparative grade/Tonnage Relationships at Boddington

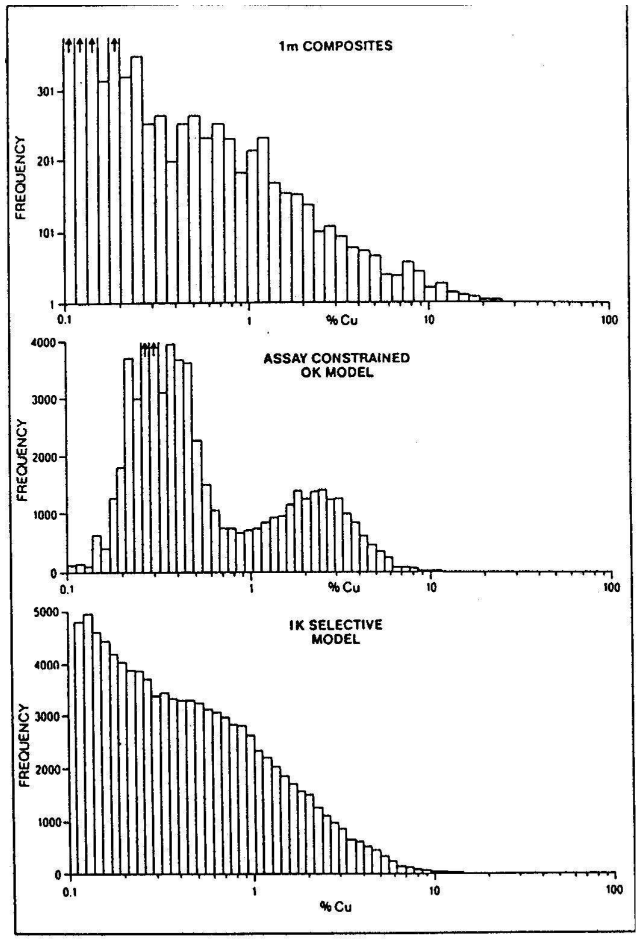

Figure 5 Artificial Bimodality Cased by use of Hard Assay Boundary

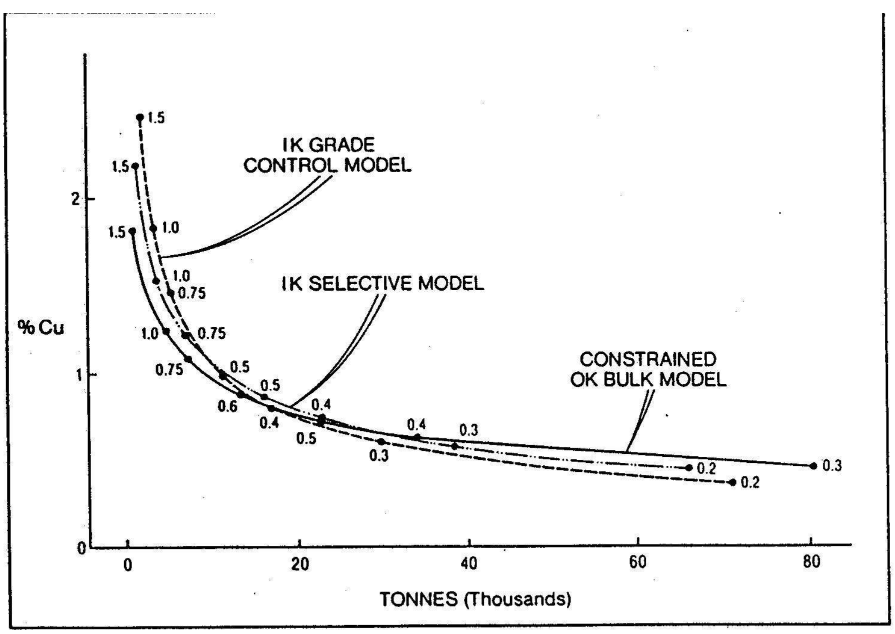

Figure 6 Grade/Tonnage Relationship for Reconciliation area at Girilambone

The use of ordinary kriging for exploration data within assay constrained boundaries simply does not give an accurate grade/tonnage curve for skew data. This is not to say that the average grade within the boundary is not correct. But if the boundary does not happen to coincide with the mining cutoff, the interpolated grade distribution cannot be used to pick the cutoff accurately.

THE FUTURE

Meaningful improvements to the tools for the next century will include visualisation techniques to assist in boundary definition. Fuzzy logic/fractals/chaos theory may be useful in recognition of geological “textural” changes which can be used to develop such boundaries.

The ability to fine tune semivariograms, or some other measure of structural continuity, interactively (on line) would assist in interpreting anisotropy as well as domain recognition.

We will always have the problem of potentially inadequate data with respect to the degree of geological complexity in a deposit. Better statistical interpretation can only be expected once better geological interpretation exists. Tools which allow dynamic experimentation by linking graphical images on the spatial database with statistical fingerprinting would allow the user better interaction with the data, so to judge better the relationships between his geological observations and the statistical characteristics of the orebody.

We should be conscious of linking disciplines and realise that the methodology cannot be rigid. We require flexibility both in our tools and in our outlook. More than anything we need new graphical techniques that will compliment our efforts to understand the link between geology, statistics and mining practices.

ACKNOWLEDGEMENTS

The management and production staff of Macraes Mining Company, Temora Gold Mine, Copperhead Mine, Boddington Gold Mine and Girilambone Copper Company are thanked for their assistance in project work and for permission to publish the results presented in this paper. Mark Thomas and Annick Manfrino-Thomas of Snowden Associates were responsible for work done at Girilambone and Macraes respectively.