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Mineral Resource Estimation

By I M Glacken[1] and D V Snowden[2]

INTRODUCTION

The process of estimating a Mineral Resource can only take place after the estimator is convinced of the soundness of the fundamentals underlying the estimation process. Thus the database of sampling, density, and other quality data for both estimation and geological interpretation must have integrity and robustness (Chapter 2); the geological data must be sufficiently complete for the definition of a geological model; the geological model itself must have internal consistency, should explain the observed arrangement of lithological and mineralogical domains, and should represent the estimator's best knowledge of the genesis of the mineral deposit; and the geological model should support the distribution of mineralisation seen in the sampling (Chapter 3). It is only at this stage that a resource model may be generated. The resource estimation process involves the definition of mineralisation constraints or geological domains, the statistical and/or geostatistical analysis of the sample data, and the application of a suitable grade interpolation technique. The final stage of the estimation process is to classify the resource according to the JORC Code (JORC, 1999 and republished in this volume, see Appendix I).

Synopsis of resource estimation techniques

Resource estimation techniques range in complexity, roughly proportional to the amount of computation involved in deriving the estimate. The simplest techniques involve assigning to an orebody intersection its own clearly defined area of influence, defined in relation to the other intersections. Such techniques are known as polygonal, area-of-influence, or nearest-neighbour approaches. Polygons may be developed in the plane of mineralisation, or may be projected onto a suitable horizontal or vertical plane with the corresponding geometric transformation. One very common version of this polygonal approach is the sectional area-of-influence method, with polygons defined on sections (perpendicular to mineralisation) extended orthogonally to the section plane halfway to the next section.

Limited averaging of grades occurs in some techniques, not common nowadays, where, for instance, triangulations are constructed about the mid-point of intersections, with the grade of each triangle being the arithmetic mean of the grades at each of its vertices. Other approaches include averaging values at the corners of other regular shapes or within grade contours.

The next step up in computational complexity is to apply some weighting function to grades surrounding a point or block to be estimated. This is attractive where a series of regular points or blocks need to be estimated in two or three dimensions for subsequent planning or manipulation. The simplest weighting function in common usage is based upon the inverse of the distance of the sample from the point to be estimated, usually raised to the second power, although higher or lower powers may also be used. Such inverse distance techniques introduce issues such as sample search and declustering decisions, and cater for the estimation of blocks of a defined size, in addition to point estimates.

Further complexity in calculation is engendered by the use of geostatistical techniques, all based upon the theory of regionalised variables developed by the French mathematician Matheron (1962, 1963). These methods all seek to utilise the spatial relationship between samples, as quantified by the semi-variogram, to provide weights for the estimation of the unknown point or block. The standard technique of geostatistics, named kriging by Matheron in honour of the South African mining engineer Danie Krige, has many varieties, but those most commonly used are the variants of ordinary kriging, the so-called linear kriging techniques.

The evolution of geostatistics in the last decade and a half has seen the development of a range of non-linear kriging techniques, based upon non-linear transformations of grades. These include the commonly used methods of indicator kriging and the various flavours of uniform conditioning and disjunctive kriging. Non-linear kriging approaches seek to estimate a distribution of grades into each point or block, thus providing some measure of local uncertainty.

The most recent development, and the most complex and computationally intensive method used in resource estimation, is that of conditional simulation. This builds upon kriging and the use of stochastic (random) sampling approaches to provide, in theory at least, a full measure of uncertainty. Conditional simulation, while honouring data values locally, overcomes many of the shortcomings of kriging methods. The negative aspects of complex approaches such as this are the time and computational power required for its implementation and the lack of simplicity, which hampers understanding and acceptance.

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All methods described above have a number of common attributes; all must be based upon a carefully defined geological model, and all require extensive validation by the practitioner. A good overview of the various techniques is given by Carras (1998 and this volume).

It should be noted that the resource estimation process, while often driven by the geoscientist, is a team endeavour, and should include contributions from mining, metallurgical, and often the commercial disciplines.

Another essential aspect of the process is quality control, including management of the estimation process and most importantly, management of the data sourced from the various disciplines.

History of resource estimation

Since the start of the modern mining era there has been an increasing use of sample data to estimate the amount of material mined or to be mined. Early mining operations had little forward planning, and consequently little use was made of exploration or mining data to estimate resources or reserves, although there was extensive use of data for grade control and for monitoring of the mining operations. The early resource estimations - which were in fact reserves - arose out of this grade control function, where, for example, underground face and raise samples were used to delineate a mining block. It was only in the middle part of the 20th century that exploration drill holes started to be used to define a form of mineral inventory. The earliest methods used were all variants of the polygonal estimator, and typically, dilution and recovery were built into the estimation process to define an Ore Reserve without first progressing through the resource stage.

As the importance of planning and scheduling of an operation's mineral endowment became apparent, the use of all types of sample data to define Ore Reserves increased. However, there was little regulation of the reporting standards and these tended to vary widely. The methods used to estimate reserves also developed, and in the 1950s and 1960s there were a number of attempts to fit simple mathematical models (such as multiple linear regression) to the sample data and thus derive simple statistical parameters such as the mean and variance of the underlying population. In South Africa some success was achieved by fitting lognormal distributions to mine data (Krige, 1978), but this failed to translate well to Australian orebodies.

With the advent of increasingly fast and reliable computers, mine planning packages, which incorporated resource and reserve estimation, were introduced from the late-1970s.

These provided for the first time the ability to generate a model of the orebody comprising a large number of orthogonal, similarly-sized blocks. Accompanying this block modelling ability the packages generally offered a variety of resource estimation techniques, including polygons (more strictly a nearest-neighbour interpolator), inverse distance estimation, and simple or ordinary kriging. Although much work was carried out in developing mining geostatistics in the 1960s and 1970s in France and in North America, kriging was not routinely used as a resource estimation technique until the end of the 1970s. The method gained a somewhat tarnished reputation due to its poor application by inexperienced practitioners, and inverse distance estimation, along with the various varieties of polygonal estimation, established themselves as the methods of choice.

The mining software packages continued to develop in power and sophistication during the 1980s, and great advances were made in the visualisation and modelling of complex geological domains. It was during this time that the first resource estimates *sensu stricto* were generated. These were then modified by the mining design and other factors to yield Ore Reserves.

Following its initial poor reputation, kriging techniques continued to be used increasingly, especially the non-linear approaches such as indicator kriging (Journel, 1983). However, a large number of resources were still estimated using non-geostatistical techniques. This polarisation continues to the present day, although some form of block model is now accepted as the norm in the majority of estimations. As computers continue to grow in power and sophistication, a number of very computationally-intensive techniques such as conditional simulation are starting to become common.

There have been many studies of the history of resource estimation and the evolution of methods over time. Reeve and Glacken (1998) describe the history of reserve and resource estimation for one large Australian mining company, WMC Resources Limited. Arvidson (1998 and this volume) describes the process of bringing together over 100 years of data to generate a resource estimate for the gold deposits of the Golden Mile in Kalgoorlie. Murphy *et al* (1998) provide an overview of the resource estimation process at the Bronzewing and Jundee gold operations, Yandal province, WA.

Lutherborrow (1999 and this volume) describes the history of estimation on the Broken Hill field and the recent development of a three-dimensional methodology.

THE RESOURCE ESTIMATION PROCESS

Assignment of domains

Once the geological model is as complete as the available data and knowledge of the setting and genesis of the mineralisation allow, the data must be coded according to its domain. A domain in this context is defined in the loosest sense, and represents an area or volume within which the characteristics of the mineralisation are more similar than outside the domain.

Hopefully the geological modelling will have highlighted a number of domains, which should conform in some way with the geology wherever possible. In many cases, the geological units are the same as the mineralisation domains, such as in many iron ore, sedimentary base metals or base metal sulphide deposits. In this case, the grade modelling is constrained entirely by the geological modelling, and the resource grade model will be a true reflection of the geology. In many other cases the mineralisation of interest does not entirely correspond to a geological unit, or transgresses geological units. This is a typical feature of structurally-controlled mineralisation, such as shear-hosted gold deposits (eg Porgera, PNG). A number of deposits, such as those in the Callie and Granites ore systems of the Northern Territory, combine elements of structural and lithological control. A further class sees disseminated mineralisation scattered widely throughout a limited range of rock types, with no clear geological pointers to the distribution of grades. Typical examples of this style of mineralisation are the large porphyry-hosted copper and gold deposits, such as those at Ok Tedi in PNG and Grasberg in Indonesia.

The resource estimation domains should honour the geology wherever possible, but where this is not achievable, some other form of domain boundary needs to be imposed. Typically this is a grade boundary defined by a cut-off grade which should bear some relation to the economics of the deposit to be evaluated, however preliminary the assessment is which needs to be made. Domains may be defined by a combination of statistical and geostatistical means, in addition to or instead of by a cut-off grade. Where grade alone is used to define the domain boundaries, then it is risky to use a cut-off grade too close to the overall economic cut-off of the deposit. If this is the case, the result is often the overestimation of grades within the domain, and the underestimation of grades outside the domain. Some deposits show a rapid change from ore to non-ore, so selecting a natural cut-off is relatively safe (eg Osborne copper-gold deposit, NW Queensland, and most of the Archaean lode gold deposits of the Yilgarn craton in Western Australia). These boundaries may be termed hard, and greatly facilitate resource estimation. The other extreme is the gradual or soft boundary, requiring much more careful treatment when estimating resources. Structurally complex deposits such as those at the Macraes gold mine, New Zealand, display a combination of hard and soft boundaries. The well-defined hangingwall of the shear zone is a hard boundary, but the footwall is gradational and areas of associated stockwork mineralisation also have soft boundaries.

It is possible, in defining domains for resource estimation, to impose several types of boundary conditions. Soft domain boundaries allow grades from either side of the boundary to be used in estimating both domains, to varying degrees. Hard domain boundaries do not permit interpolation of grades across domains. One-way soft domains are often used in estimation, data within a high-grade domain is not used to estimate within an adjacent low-grade domain, but estimation of the high-grade domain will use data from within the low-grade domain. Such one-way boundaries introduce conservative bias and avoid artificially sharp grade boundaries. More useful are partly soft domain boundaries, where only limited crossing of domain boundaries is allowed.

Stegman (1999 and this volume) discusses the effects of domaining on resource estimation in the Cobar region of New South Wales.

Finally, it is worth bearing in mind that several different types of domain may be used in the same region. A typical example is the use of oxide, transition, and primary domains to allocate specific gravity in an oxidised mineral deposit. Similarly, metallurgical domains may be used in addition to geological domains to define areas of differing metal recovery. Often one set of domains is used for estimation and another for mining/metallurgical purposes. As many different types of domain as are needed to define the resource and to provide information for reserve estimation should be used.

Data analysis

Statistical analysis may help decide the nature of the domain boundaries. The analysis should include studies of how grades change at domain boundaries.

Once a series or several series of coherent domains have been defined, the numerical characteristics of the mineralisation in each of these areas should be described. This will not only assist with the choice of a grade interpolation method, but will also highlight any special data treatments (such as grade cutting) which need to be applied. Where there are several minerals or variables of interest, statistical analysis will reveal any patterns or correlations between them which need to be taken into account. Statistical analysis should take place within the domains defined either by the geological model or by other approaches.

One prerequisite of data analysis is that the samples all represent an equal volume. This is called the support of the sample. The accepted way of ensuring equal support of all samples within a domain is to composite the samples (usually drill- or interval-related data) into equal lengths. There are various algorithms for compositing, but the practitioner should always check that the results are as expected.

Another problem, which needs to be tackled before data analysis can take place, is preferential clustering of data, which not only affects statistical analysis but can also bias the variography. Since there is a natural tendency to drill more holes or take more samples of the higher grade portions of the mineralisation, clustering or irregular representation of samples is a real possibility. Domaining might be necessary to correct this. Alternatively, various declustering approaches are available to ensure that each sample represents an equal volume for statistical analysis. Failure to take heed of preferential clustering of data may lead to biased results. Note that it may be desirable to treat different drilling types (eg diamond and reverse circulation) differently within the same domain.

If sampling is done on fixed lengths, then compositing should be on multiples of the original sampling interval to minimise unnecessary smoothing. Zonal compositing (that is, compositing within domains) prevents this in many commercial packages, as composites commence after a change in zone at an odd interval, not at the start of an original sample, especially where zones are not defined on sample intervals. The method of compositing adopted should take into account the style of mineralisation and boundary requirements. For example in a narrow vein, hard boundary environment, it is essential to composite by zone to avoid over- or under-dilution. This is of less consequence where the boundaries are gradational.

There are some schools of thought that believe that composites should always be equal to the height of the mining bench. There are advantages in employing bench compositing, in that the input data is fully diluted to the bench height. However, where drill holes are angled at various orientations with respect to the mining bench, this could result in different support lengths for different composites, particularly when drilling is orientated close to horizontal. Downhole compositing ensures that each sample represents the same support. Assay lengths should not be split into smaller composite lengths, as this results in an artificially low variance for the modified support as adjacent composites could be identical in value. Issues of bench compositing are starting to have less importance as true three-dimensional methods of resource estimation predominate, and in this paradigm each composite represents a point in three-dimensional space, irrespective of orientation.

Once compositing and declustering have been applied to the data, statistical analysis can take place. There are no recipes for this, but a good summary of statistical analysis techniques is given in Isaaks and Srivastava (1989). Desired outcomes from statistical analysis of the data would be:

- depiction of any trends evident within the domains;
- depiction of data distributions in both histogram and cumulative probability form;
- a decision as to whether a distribution-based interpolation technique may be used;
- definition of any data subsets within each domain;
- comparison of different sample types;
- establishment of the basis for any top cuts to be applied;
- choice of thresholds for indicator kriging, and
- establishment of any relationships between multiple variables.

Statistical analysis may indicate that some domains have very mixed populations, eg excessively high coefficients of variation or multi-population probability plots. This may signal the need for more or different domains or, if it is not possible to separate out the populations, indicator techniques may be necessary for variography and kriging.

Where there is a positive correlation between the bulk density of the ore and the grade of the minerals of interest, typically in massive sulphide deposits, the bulk density should be involved in the actual estimation process, in other words, sample intersections used for grade estimation should be weighted by density as well as by length. Another option which is often considered is the direct interpolation of bulk density along with the grade variable(s). This method of density weighting is used at many base metal deposits (eg Kambalda, (Glacken *et al*, 1998 and this volume)).

Geostatistical analysis

As a precursor to any of the various kriging or conditional simulation techniques, spatial (geostatistical) analysis of the domained data - that is, the calculation and modelling of semi-variograms - is an obvious and necessary step. However, the analysis of the continuity of data values in three dimensions is also a very useful precursor to almost any form of estimation, as it defines, at the very least, the classical 'range of influence' of the data. Knowledge of this can and should have a bearing on the choice of a suitable grade interpolation technique. For instance, the direction and magnitude of the ranges may be used to define grade search parameters or the maximum size of polygons of influence.

The generation of semi-variograms and their subsequent modelling should reveal the structure of spatial continuity of the data, and should confirm geostatistically any geological trends previously modelled or noted (see Chapter 3 for details of geological interpretation techniques). The practitioner should always seek a geological explanation for the principal directions revealed by semi-variogram analysis. Quite often such a step will reveal some subtle controls on mineralisation not immediately evident in the geology.

Geostatistical analysis will also reveal any anisotropy in the domains of the mineral deposit and seek to quantify the magnitude of that anisotropy. The anisotropy may be represented by the same total variation but at different ranges in the various directions (geometric anisotropy), or by different magnitudes of the variation in different directions (zonal anisotropy). The analysis should also seek to verify the decision to use hard or soft domain boundaries, and should confirm the amount of random variation, whether due to sampling problems or due to inherent randomness in the data, in each direction.

Although variography should not be used as a substitute for geological interpretation, it can indicate whether the geological model is appropriate.

Indicator variography may demonstrate that the amount and direction of anisotropy varies with grade, eg high-grade veins may have a different orientation compared to the bulk of the mineralisation.

Finally, the definition and modelling of semi-variograms will help with the definition of the basic block size to be used in any block modelling techniques, and will provide information for the aggregation of grades into larger block sizes if required.

Some Australian operators use variography to determine the range of influence and hence filter size for inverse distance interpolations.

Geostatistical techniques for data analysis are presented by Coombes (1997), Longley-Sinitsyna and Snowden (1997) and Vann and Sans (1995).

The volume model

Prior to grade estimation, it is necessary to convert the geological model and/or the domain model into a physical, usually three-dimensional, representation of the volume of mineralisation to be estimated. Common practice is to define a block model, comprising a series of orthogonal cuboid blocks either of the same size or of subsets of a nominated 'parent' block size. This is usually a semi-automatic process, but generally requires a confining shape in which to generate the blocks. Typically this is given either by a three-dimensional enclosed solid or by a series of surfaces. These are generated by wireframing strings of points on section or plan, or by triangulation of a series of points and strings into a digital terrain model, more commonly termed a surface. Surfaces may also be interpolated from the raw data by a number of surface-fitting techniques.

Modern mining software has advanced to such a degree that almost all of the major packages provide moderate to excellent tools for defining both the three-dimensional shapes and for filling them with blocks. Key decisions for the practitioner include:

- How large should the blocks be compared to the data?
- What should the relative shapes of the blocks be in the three dimensions?
- How complex should the wireframes be?
- Should subcelling be introduced, or will the extra resolution produce too many blocks?

While the advantages of a block modelling approach are that it provides the framework for a good local estimation, that it provides a model which lends itself readily to reserve estimation, and that it allows the modelling of mining selectivity, not all resource estimation is carried out to this detail. In some cases a simple cross-sectional area of influence model is appropriate, or a nearest-neighbour (polygonal) approach.

Unsmoothed grade estimation

As mentioned above, despite the speed and power of modern computers and the sophistication in estimation algorithms which this allows, many practitioners carry out grade estimation using unsmoothed or polygonal techniques. The essential aspect of all of these algorithms is that each grade, or series of grades in a defined intersection, is allocated unaltered to a specific area of influence. The simplest means of allocating grades is via polygons of influence, which are generated by constructing the perpendicular bisectors between adjacent samples or intersections. These are generally constructed in two dimensions on composited intersections, and rarely in three dimensions. In the block modelling context the polygonal approach is represented by the nearest neighbour approach, in which each cell or block to be estimated assumes the grade of its closest sample within the defined domain. This in effect generates three-dimensional polygons. Although conceptually very simple, many resource and reserve systems based upon the polygonal approach are very complex in their treatment of individual samples and their geometrical relationship to the ore surface. Many systems involve projection onto either a horizontal or vertical plane and the subsequent geometric manipulation of areas and volumes.

A very common adaptation of the polygonal approach is the cross-sectional resource estimation method. In this approach, sectional interpretations are constructed, generally orthogonal to the strike of mineralisation. Each separate ore intersection on each drill hole is allocated its own volume of influence, which usually extends halfway to the next drill hole up and down dip, and halfway to the next section in each strike direction.

An adaptation of the polygonal approach in narrow orebodies is the use of accumulations (sometimes termed service variables). Metal accumulations are the product of grade and thickness. In this approach the accumulation is estimated, and the thickness is estimated independently. The final grade is obtained at each point by dividing the accumulation by the thickness. The accumulation approach only works well where there is no correlation between grade and thickness, and also requires the spatial orientation of the samples to be taken into consideration as true (normal to dip) ore thicknesses are required. It is worth noting that the accumulation and thickness variables can be estimated using any technique, including geostatistical methods.

The advantages of the polygonal, nearest neighbour, and sectional methods are their simplicity and theoretical ease of application (although, as noted, the geometrical manipulations may be extremely complex). Another bonus is the speed of obtaining a result. The polygonal estimator also has the added advantage of being the perfect declustering technique for irregular data. However, there are a number of distinct disadvantages, including the lack of applicability of the method to thick, non-tabular bodies, and the assumption of an unrealistic model for grade variation. The major objections by advocates of geostatistical techniques include the issue of ignoring sample support (every sample has a different support, equivalent to the size of the polygon or the area of influence) and possible conditional bias (high-grade areas are overestimated and low-grade areas are underestimated). This is discussed by David (1977, p309).

Smoothed grade interpolation

Most resource estimation techniques, and most in common practice today, use some form of grade smoothing to interpolate values into a block based upon surrounding samples.

These fall neatly into two categories - the non-geostatistical methods and the geostatistical methods.

The methods of grade interpolation use some relationship between the distance of a sample from the block centre and the weighting which it is given. The most commonly-used approach weights each sample by some power of the inverse of its distance from the block to be estimated, usually the second or third power. The power chosen is somewhat arbitrary, although it is well-known that the lower the power, the greater the smoothing of grades. Higher powers of inverse distance tend to approximate a nearest neighbour approach, with distal samples receiving almost no weight.

The geostatistical approaches to grade interpolation all rely on some form of kriging, whereby the weights given to each sample are derived from the semi-variogram model, which defines the continuity of grades in two or three dimensions. These geostatistical methods may in turn be subdivided into three classes - linear kriging, non-linear kriging, and simulation. All geostatistical methods rely to a lesser or greater extent on the assumption of stationarity, which is seen as the decision to pool data within a given area or domain, and not as a hypothesis which can be proven or disproven.

Linear kriging techniques are the simplest to apply, and centre on simple or ordinary kriging and their variants. These techniques are generally based on classical parametric statistics, which are affected by the distribution of the grade population underlying the data. Ordinary kriging is more resistant to departures from the assumption of stationarity than simple kriging, and is optimal for normal or Gaussian distributions of data, although still effective in other circumstances.

Non-linear techniques have gained in popularity in the last ten years, and address some of the deficiencies of the linear techniques. All non-linear kriging techniques are based upon non-linear transformations of the sample data such as the natural logarithm, the Gaussian (normal scores) transform, or the indicator transform. The most widely-used non-linear techniques are the various flavours of indicator kriging, uniform conditioning and disjunctive kriging. A comprehensive review of most non-linear kriging approaches is given by Vann and Guibal (1998 and this volume). The perceived advantage of non-linear kriging techniques is firstly that they are able to cope with highly-skewed or mixed distributions of data (in other words, data most commonly seen in practice) and

secondly, that they are able to derive local distributions of uncertainty which lead to a practical estimate of resources above a range of cut-off grades. Such estimates are known as 'recoverable resources', and while representing the correct support for mining still need to be subjected to the reserve process. It is fair to say that indicator kriging is the most easily understood and the most commonly applied of all the non-linear kriging techniques; overviews of indicator kriging are given by Glacken and Blackney (1998) and Khosrowshahi *et al* (1998). Practical implementations of non-linear kriging techniques are presented by Elliott *et al* (1997 and this volume), Collings *et al* (1997 and this volume), and Matthews *et al* (1999).

Indicator kriging is a reasonably robust technique in that considerable changes in variogram parameters can be withstood before greatly affecting estimated grades. Some other geostatistical estimation methods may be much more dependent on the accuracy of the variogram models. As gold typically has difficult variography (because of mixed mineralisation styles and often noisy sampling and assaying) robustness is desirable.

CONDITIONAL SIMULATION

Conditional simulation, which typically uses a kriging technique combined with a Monte Carlo sampling approach, has the potential to enhance most of the geostatistical approaches currently used. Conditional simulation produces a number of equally-likely pictures of the grade estimation, each of which honours the distribution and spatial continuity inherent in the input data. Conditional simulation also has the ability to reproduce the level of variability in the samples, in contrast to other smoothing methods which reduce the variability. Simulations allow the practitioner to choose a result which is commensurate with the objective of the investigation, and have the ability to incorporate the risk and cost profiles of the operation under investigation. An overview of conditional simulation for resource estimation is given by Khosrowshahi and Shaw (1997 and this volume). Practical aspects are presented by Rossi and Alvarado (1998), Dowd (1996), and Glacken (1996). Schofield (1993 and this volume) describes a particular use of conditional simulation, that of identifying the optimum drilling density.

Conditional simulation may be most useful where data are closely spaced (ie ample conditioning data) and may be seen as supplementing other estimation methods (ie by providing sensitivity analysis) rather than replacing them.

The key aspect of simulation which differentiates it from estimation is the consideration of probability or risk. It is possible to derive the probability of exceeding any given cut-off grade, or to define true confidence intervals of a specified degree of certainty around any single figure. The risk or confidence is a function of the production unit; the chance of achieving target grades or blends is greater for large parcels of ore (such as six months production) than daily production units. In any case, however, simulation allows the quantification of that risk.

Volume-variance, sample search and block size issues

It is well-known that there is a volume-variance relationship, whereby grades based on a sample support are more variable than grades based on a block support, and moreover that the larger the block, the less variable, or smoother, the distribution of the grades. It is thus important to model the appropriate block size to achieve a representative distribution on which to predict the grade/tonnage relationship for a given mining scenario.

Whatever the estimation approach adopted, all techniques which seek to interpolate grades into blocks (except the nearest neighbour method) depend on the sample search procedure. The methods by which samples are selected for subsequent weighting are critical to the process, and in some cases (eg Carras, 1998 and this volume) are of more consequence than the estimation algorithm itself. A good sample search plan should have some or all of the following features:

- declustering of data via octant or quadrant selection;
- restrictions on the number of samples from one drill hole;
- minimum and maximum numbers of samples specified for search:
- preferred search directions (ie anisotropic search); and
- restriction of the influence of high-grade samples.

In common with the sample search plan are issues of block size for interpolation into block models. The block size to be used should ideally bear some relation to the mining equipment planned or used, often referred to as the selectivity. The concept of the selective mining unit is the smallest parcel of ground on which mining decisions, such as the allocation to ore or waste, may be made. The block dimensions should also be considered in relation to the sampling grid; blocks that are too small will result in oversmoothing of the sample data and subsequent very low precision results.

Oversmoothing results in conditional bias, whereby high-grade blocks are underestimated and low-grade blocks are overestimated. A number of tools are available to decide on a suitable block size - these are discussed in some detail by Krige (1996).

Undersmoothing results in a form of conditional bias whereby high-grade blocks are overestimated and low-grade blocks are underestimated. Elliott *et al* (1997 and this volume) describe the change in the grade/tonnage relationship depending on whether a model is based on kriged block estimates (smoothed) or raw assay data (unsmoothed). Reconciliation of the estimates with the actual head grades achieved during mining, plus the eventual processing of low-grade stockpiles, illustrates the sensitivities of the volume-variance effect in this case study.

Conditional simulation provides some useful tools to check or determine optimal block sizes and the degree of smoothing inherent in a resource. Small-scale simulations on representative areas or domains allow the change of support to be determined more accurately and locally than using one of the global techniques. The use of a simulation approach also allows the

determination of the selectivity and inherent smoothing in an estimated model. A case study using this application of simulation (Glacken *et al,* 1998 and this volume) details how a kriged model can be calibrated to achieve the desired selectivity.

Checking the resource

Validation of the resource estimate can be undertaken using various tools including:

- graphical plots of sections/plans showing input data and block grade estimates;
- histograms of input and output grade distributions within domains;
- input and output mean grades within domains; and
- generation of resource estimates using alternative algorithms or approaches.

The graphical validation plots of the resource need to make geological sense and show accord with the geological model. If not, further work must be carried out to resolve any anomalies.

Once again, the importance of clustering on data statistics should be taken into account as this can bias the mean of the input data. It is also important to note that the mean grade obtained can also be biased if the population is skewed in distribution, and the input mean grade needs to be corrected accordingly. This is typically done by applying a top cut. If the data is perfectly lognormally distributed (ie the logs of the data show a normal or Gaussian distribution), the Sichel mean is a better estimator of the unbiased population mean.

The best validation tool for any resource estimate is reconciliation with production (see Chapter 8). Comparisons between the grade/tonnage curves for the resource model and the grade control model within a given identical volume and with the production records for the corresponding mining period will give an operation the greatest confidence in the merit of the resource model.

Resource classification

The final task in resource estimation is to classify the resource - this not only imparts levels of confidence in the results, but also dictates which classes of Ore Reserve may be generated by subsequent modification of the resource figures. The task of resource classification under the JORC Code (JORC, 1999 and also republished in this volume, see Appendix 1) is the duty of the Competent Person, and therefore is ultimately a subjective duty, but notwithstanding this, the resource classification should ideally be based upon as many objective factors as possible. Clearly those factors related to the data and its configuration are of most importance, but these may be tempered by overriding geological, mining or data-related issues. Chapter 9 discusses reporting and regulatory requirements.

At the simplest level, resources may be classified on the basis of the overall drill spacing within the various domains or regions of the deposit. This is easily understood, but may not take into account any anisotropy which exists. Another approach is to consider the average distance from the block centre of those samples used to estimate that block, or simply the number of samples defined inside the search volume.

Another technique expands search volumes during multi-pass estimations, with those blocks being estimated by the most distal samples having the lowest-confidence resource category.

One of the more useful criteria for resource classification is the kriging variance or error arising from estimation. While useless as an actual grade confidence measure (unless the data is strictly normally distributed), the kriging variance depends on the arrangement and continuity of samples around the block, and thus is a good indicator of overall sample spacing which takes anisotropy and sample clustering into account. Other numerical approaches include the regression coefficient and kriging efficiency measures proposed by Krige (1996).

There is a move in some sectors of the industry towards the use of conditional simulation as a resource classification aid (Guibal, 1997; Snowden, 1996 and this volume). Since simulation quantifies the grade confidence, for a given block size, in addition to considering data position and continuity, it will provide more information to assist resource classification than numerical indicators such as the kriging variance alone. Any simulation-based resource categories must be tempered by detailed consideration of non-grade factors, as with any classification.

In most cases the resource classification will be based upon a combination of criteria, numerical and geological, with overall manual override by the Competent Person (Snowden, 1996 and this volume).

Overview papers

A number of papers included in this volume provide an excellent overview of the entire resource estimation and classification process. Collings *et al* (1997 and this volume) describe the geological modelling, resource estimation and classification aspects of a sedimentary-hosted iron ore deposit, while Lutherborrow (1999 and this volume) charts the evolution of a new resource estimation system at the Broken Hill deposit. A similar historical perspective is presented by Glacken *et al* (1998 and this volume) for the Kambalda nickel mines.

Moorhead *et al* (1999 and this volume) present the resource estimation procedures at the Cadia Hill mine in New South Wales. Pocock (1999 and this volume) describes why resources at the Peak gold deposit, Cobar, NSW, have always been underestimated. The evaluation and classification of mineral sands resources is comprehensively described in Lee (this volume).

OUTLOOK

The two developments that will most affect the future of resource estimation are technology and the introduction of more sophisticated estimation/simulation algorithms. The power of computers still continues to double roughly every 18 months, both in sheer numerical computational power and in graphical processing ability. This has greatly affected, and will continue to affect, the resource estimation procedure. Real-time three-dimensional rotation of orebody and development models and pit and underground 'fly-throughs' are now commonplace, and this virtual reality interaction with models will continue and increase both speed and the depth of modelling features.

Developments in computing power in the last five years have made such techniques as conditional simulation routinely possible, and further speed increases will expand the breadth and depth of such techniques which are available to the practitioner. Conditional simulation for sensitivity and risk analysis will become a routine tool in most resource estimation. The increase in graphical processing power will also make possible the simultaneous real-time visualisation of multiple simulated models.

Although the current generation of mining software packages is highly sophisticated and will continue to increase in complexity, the changes will be evolutionary rather than revolutionary. A new class of mining software will start to emerge, combining powerful database facilities, extensive modelling, visualisation and virtual reality features, and incorporating sophisticated software modules such as finite element analysis, open pit and underground optimisation, interactive data analysis, detailed cost and financial modelling, mining and process simulation, and risk analysis, all centred around a three-dimensional model or series of models of the orebody.

Outside of the computer, the development of rapid and highly-accurate spatial positioning systems such as differential GPS are already affecting grade control and will start to impact on resource estimation as more data becomes available more quickly. Depletion of resource models by excavation volumes will become quicker and easier, leading to monthly or more frequent resource updates and the commensurate flow-on effects on scheduling and forecasting. Remote assaying technology will provide instantaneous turnaround for sample data. The resource models of the future will incorporate many diverse data types, collected and processed in real time.

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