Errors and Uncertainty in Ore Reserve Estimates — Operator Beware

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ABSTRACT

Ore Reserves are key mining company assets and their reliable estimation is crucial for both feasibility studies and the day to day operation of a mine. The reserve is based on the Mineral Resource after the application of certain technical and economic parameters. Engineering aspects of reserve estimation can be accurately determined to ±10 per cent, however the majority of project risk will revolve around the resource. A final Ore Reserve generally contains a set of figures quoted without reference to its potential errors. Rarely are overall confidence limits quoted and, if they are, they often do not take into account many of the factors that cause uncertainty in the grade and tonnage estimates. There is thus an unquantifiable risk, which the operator should be aware of. This paper presents a review of the possible sources of error that might occur during the various phases of an exploration and estimation programme which are carried through into the Ore Reserve and hence mine design.

INTRODUCTION

The reliable estimation of Ore Reserves is critical to all mining operations irrespective of size or commodity (Annels, 1991; Stone and Dunn, 1996; Sinclair and Vallée, 1998; Stephenson and Vann, 2001). This is particularly pertinent to underground mining operations where margins are often tight, and the technical challenges and capital expenditure involved are nearly always greater than for open pits.

The estimation of Ore Reserves is a process involving the estimation of Mineral Resources and the application of various technical and economic parameters. The consideration of errors and uncertainty during estimation is critical during a feasibility study or at the mine site. In general, different resource models will be used for feasibility study Mineral Resource and Ore Reserve assessments than for short-term grade control. The feasibility study modelling is based essentially on exploration-derived data, while the short-term models are supplemented with additional close-spaced grade control information. Errors generated during the feasibility study will often still be present when completing production-based estimates, which will of course have their own associated errors. These errors can present the mine operator with significant problems when it comes to reconciling the Ore Reserve with actual mine production.

The estimation of Mineral Resources is concerned with geological data collection (drilling and mapping); sampling and assaying; geological interpretation and modelling; and grade/tonnage estimation. Ore Reserve estimation depends on the accurate estimation of Mineral Resources; selection of the scale, method and selectivity of mining; estimation of mining dilution and recovery (extraction and planned and accidental losses); assessment of the amenability to processing and metallurgical recovery; prediction of commodity prices/markets; project economics and the estimation of breakeven or operational cut-off grades; health and safety concerns; environmental constraints; legal and taxation constraints; and political stability. The engineering aspects of Ore Reserve estimates can be generally be determined to ±10 per cent, however the majority of project risk will revolve around the Mineral Resource estimate. Different types of resource and reserve estimates will be encountered during the development of a mining project. These range from *global* to *local* estimates of both resources and reserves.

Global resource estimate – the estimation of the global resource is the first step in the determination of a mineable reserve for an orebody and its reliability is dominantly controlled by the amount and quality of both geological and grade data. The objective is to obtain an estimate of the grade-tonnage curve within a deposit defined by geological and/or grade boundaries from within which representative samples have been taken.

Global reserve estimate – the aim of the global reserve is to determine the amount of mineable material that can be recovered from the global resource following the application of cut-off grades, a selective mining unit size and technical constraints specific to the mining method applied. Global reserves are the basis for the feasibility analysis of the project. At this stage the grade-tonnage curve generated is for blocks of size roughly equal to the drill spacing, whereas the size of the selective mining unit is normally much smaller.

Local resource and reserve estimates – estimation of local resources and reserves is performed as part of detailed mine design and scheduling undertaken during both feasibility and pre-production planning stages. At this stage more accurate estimates of the grade of individual mining blocks are required. If adequate data is available geostatistical techniques will generally provide the best estimation method here provided that the block dimensions are not too small. The best local estimates will be obtained by kriging blocks of similar size to the drill spacing and estimating local grade-tonnage curves that define the selective mining units within the larger blocks.

Grade control reserve estimate – the grade control reserve estimate is undertaken during production and is the basis for the final decision as to whether a block should be mined or not. It is thus of great importance to the mine operator. At this stage more detailed sampling information will be available to undertake the estimate into smaller blocks. In the presence of closely spaced samples and suitable geological control, geostatistical methods often out-perform conventional methods. Whichever estimation method used, the high data density gives greater confidence to the estimate.

SIGNIFICANCE OF ORE RESERVE ESTIMATION ERRORS

Burmeister (1998) reviewed 35 Australian gold operations, which were started in the period 1984 - 1987 and found that two thirds of them had not achieved targeted gold production in the first full year of production. Only two out of the 35 achieved their projected recovered grade. Knoll (1989) and Clow (1990) examined Canadian gold mining operations and found only a few had lived up to original expectations. A similar exercise in North America attributed 20 out of 39 failures to Ore Reserve issues. The two reasons most commonly identified in these and other cases are related to poor grade estimation and inadequate assessment of dilution and mining losses.

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The economic consequences of errors in reserve estimates can potentially be disastrous. A ±10 per cent error in grade estimation is not uncommon and is generally regarded as acceptable for an underground operation. However in some cases, production/Ore Reserve reconciliation will show errors of ±50 - 80 per cent. When it is considered that, even for a good operation, production costs are at least 50 - 75 per cent of the mine site revenue, it can be seen that even a ten per cent decrease in grade can translate to a 20 - 40 per cent decrease in operating surplus. That translates to the bottom line in a cash flow sense and can generate an accounting loss, depending on the proportionate level of amortisation and depreciation charges. It can also render a financially stretched project non-viable.

A second consequence of serious error is the need to produce a new estimate, which may involve a significant reduction in the reserve tonnage. Unit capital charges are then increased to a level that may generate an accounting loss and a negative return on original investment.

In the experience of the authors, the downgrading of resource estimates and problems during due diligence, audit and optimisation studies are usually related to one or more of the following: sample recovery, preparation and/or assaying, combination of sample sets which are incompatible; poorly understood geological and/or grade continuity; inappropriate resource estimation techniques; inadequate determination of bulk density of ore and waste and poor assessment of geotechnical parameters.

UNCERTAINTY IN MINERAL RESOURCES AND ORE RESERVES

Mineral Resource and Ore Reserve reports generally contain a single set of figures without reference to, or quantification of, the potential inherent errors in these estimates. Rarely are confidence limits and expected levels of accuracy quoted and, if they are, they often do not take into account many of the factors that cause uncertainty in the grade and tonnage estimates.

Tonnage estimation uncertainty

The uncertainty in estimating tonnage is dependent upon a number of factors including those discussed below.

Definition of the deposit boundaries

Geological boundaries may or may not be well defined. In deposits with sharp contacts the geometry may be relatively simple, though there could always be uncertainty caused by lack of information, for example on the location of faults. Other deposits, such as porphyry copper or disseminated gold orebodies, have boundaries that are poorly known, and are determined by mineral grade rather than by any particular geological property. Where contacts are gradational, the tonnage itself is crucially dependent upon the cut-off grade chosen, and thus indirectly on the economic parameters. Critically, change in product price will change the reserve tonnage. This can be recognised and allowed for, to some extent, by the use of grade-tonnage curves, but there is not necessarily a simple relationship between metal price and cut-off grade. For underground mining, the delineation of the resource boundary may itself be controlled by the selected cut-off grade.

Bulk density

Bulk density is defined as the density of material that includes natural voids. It can either be reported as the *in situ* bulk-density (includes natural water content) or the dry bulk-density. The determination of bulk density for resource estimation is all too often overlooked. In many cases inadequate numbers of determinations are made or, even if they are, the variability is not always taken into account in the ensuing resource/reserve estimates. This variability may relate to changes in the degree of weathering and oxidation or to changes in host rock alteration or in the relative proportions of ore minerals. The use of incorrect bulk density assumptions may not lead to order-of-magnitude errors, but will bias the reported resources and reserves, and even a few percent error in estimates can sometimes be a very significant factor in determining the economic viability of a project (Lipton, 2000). Even though the geometry of a deposit may be well established, the computation of tonnage depends on knowledge of the ore bulk density.

Interpretation uncertainty

In the estimation of reserve volume and hence tonnage within a modelled resource, it is necessary to make a decision on what parts of the resource should be considered as Proved or Probable Ore Reserves and what is outside the Ore Reserve. None of the current standards give any guidance on how to do this quantitatively. It is a matter that is left to the individual Competent Person. Many different approaches have been adopted, such as relating the reserves tonnage to defined distances between drillholes, or using threshold values of geostatistical estimation variance. However, there remains no generally accepted standard method of defining the boundary for Measured and Indicated Resources or, Proved and Probable Reserves.

The uncertainty in resource tonnages is of relatively little importance, since it is always possible to define the resource more widely or more narrowly by including more or less uneconomic material that will never form part of an Ore Reserve. However, it is crucial to know the magnitude of uncertainty when reporting the Ore Reserves. Unfortunately, although grade-tonnage curves may be produced and used during the evaluation process, the expected degree of uncertainty in reserve tonnage is rarely reported in the final figures used for mine planning or financial purposes.

Grade determination uncertainty

The estimation of grades has been recognised as challenging for many years. Methods such as polygonal and sectional estimation have become discredited over the past years, though are still occasionally used in early exploration stages and even at the production stage (Dominy and Annels, 2001; Dominy and Hunt, 2001). Geostatistical methods are now far more widely applied for resource estimation worldwide. There are really two main sources of error in grade estimation:

1. sampling error, and
2. estimation error.

Sampling errors

The effects of poor sampling regimes at any stage of a mining operation can introduce unpredictable random errors or negative or positive bias into the estimate, which in the authors view may be of up to ±30 per cent. It is unfortunate that this source of error is virtually ignored in many estimates. The total error is a composite of a number of different sources of error (sampling representativity, sample bias, sample preparation, analytical error, and transcription errors). It is of particular significance in gold and diamond deposits, or any mineral that has a highly skewed distribution. Each source of error results in effective blurring of the true grade distribution, usually resulting in a more uniform and symmetrical (less skewed) distribution. Although this may make the numbers more tractable in subsequent estimation procedures, it can also ignore the expected variability of a deposit – causing significant problems in subsequent selective mining and reconciliation. Certain of these errors can be minimised through good work practice (QA/QC), correct equipment, suitable physical sample selection (representative sampling) and handling (dealing with segregation). The importance of well-designed and implemented sampling programs has been stressed by numerous authors (Long, 1998; Vallee, 1998; Shaw *et al*, 1998).

Estimation error

Geological modelling

The treatment and subsequent interpretation of geological data forms the basis of the Mineral Resource estimate. Information that needs to be determined to assess the impact of the geology on the modelling of the mineralised zone are grade continuity/variability; geological continuity/variability; effects of faulting fracturing/jointing and/or folding; definition of assay hangingwall and footwall and ore envelope; barren or low-grade internal zones; metallurgical characteristics; and ore mineralogy, chemistry and petrography.

Consideration of errors is never so important than during the estimation of local reserves prior to, or during production. Errors introduced by grade and geological continuity are closely related to the local model block dimensions relative to the spacing and density of the drill holes. We need to know whether all faults have been intersected and what their potential effect on the mining block will be. There is always a possibility that some faults have remained undetected because of excessively wide hole spacing or an unsuitable hole inclination. We need to know the impact of folding and whether this has resulted in duplication of horizons within the mineralised zone, incomplete intersections and errors in true thickness estimates near fold axes.

The definition of the orebody limits relates to whether the assay contacts are sharp (hard) or gradational (soft) and whether the ore envelope can easily be defined between drill holes. If the orebody limits are highly irregular and the mineralisation variable, then the construction of the envelope is a subjective process liable to large discrepancies between correlations produced by different geologists. Barren or low-grade internal zones can also introduce further complication and hence errors into the estimation process. Accurate boundary definition is required to constrain the block modelling process and prevent marginal smearing and grade dilution.

Failure to define metallurgical zones precisely may result in errors in the estimation of the relative proportions of different material types, some of which may be refractory in character. Similarly, failure to identify changes in mineralogy or mineral chemistry may result in over-evaluation of intersections for such changes may impact on metallurgical recoveries and/or the levels of deleterious elements.

Selection and application of the estimation method

The selection of the estimation method is one of the fundamental decisions made in the resource estimation process. Methodologies are either:

1. conventional (eg polygonal, sectional, triangular or inverse distance weighting); or
2. geostatistical.

The effects of incorrect estimation are well documented and alone could lead to errors of up to ±40 per cent in the estimate. For a given orebody, the estimator needs to look at the grade interpolation method in terms of its suitability for production of a global or local resource or reserve, its ability to deal with geological and grade continuity issues, stratigraphic and lithological changes and selective mining.

Whichever estimation method is used, it must be chosen and applied within a strict framework of geological understanding. Geology should guide resource estimation, not resource estimation guiding the geology (Sinclair, 1998; Duke and Hanna, 2001; Dominy and Annels, 2001). Geological interpretations are continually evolving components of the resource estimation process because new information is continually becoming available as exploration, evaluation and exploitation proceeds. If the resource estimation process is based on high-quality data, whose interpretation is controlled by geology and statistics, then it has a good chance of being close to the truth.

Mine planning uncertainty

Assessment of mining constraints

An Ore Reserve estimate is based on the Mineral Resource overlain with mining, processing and other related factors (Roscoe, 1993; Rickus and Northcote, 2001). In general it is that portion of the resource that can be extracted and processed at a profit. For underground mining operations critical inputs include thickness, dip, continuity and spatial relationship of mineralised zones, the regularity of wall contacts and the strength of the ore and wallrocks. Ore Reserves are strongly dependent upon various considerations including the size of ore blocks in relation to SMU's; minimum stoping widths; choice of stoping method; dilution (planned versus unplanned); mining recovery factors; metallurgical recovery; stope and pillar stability; and accessibility. Failure to account for these inputs or unrealistic estimates for these criteria/parameters can lead to substantial errors in the reserve estimate.

Ore block size is dependent on sample density and on an estimate of the geostatistical ranges and degree of anisotropism. The size of anticipated selective mining units (SMU's) might be considerably smaller than the ore blocks used to calculate the Ore Reserves. Thus corrections must be made to allow for this, as the variability of grade amongst SMU's will be considerably greater than that for the host ore blocks. This could seriously affect the estimated ore and waste proportions and the actual variability in the feed, and hence the operation of the plant and the viability of the whole operation.

Many Ore Reserve estimates do not carry explicit warnings that they relate only to a particular choice of specific mining method. However, the selection of mining method (eg shrinkage, block caving, longhole or cut-and-fill) is of crucial importance in defining what is both technically possible to mine and what is actually profitable to mine (Kaesehagen, 2001). On exactly the same resource, it is possible to define a range of different mining options each with its own estimated reserve tonnage and average grade. The different scenarios may have different economic cut-off grades and some may have lower tonnage and higher grade, others larger tonnage and lower grade. Open pit and different underground mineable reserves may even be geometrically quite different due to the differences in physical constraints of each mining method. The selection of the best mining option may often be far from obvious. Indeed, the best mining option may be different in different economic scenarios. What could be a viable large open pit mine when the gold price is high might, with lower gold prices, better be defined as a small underground mine extracting high-grade pockets of ore – and some of these pockets could be at depths which would exclude them from the open pit reserve.

One of the most common errors is the estimation (usually under-estimation) of dilution which in itself can lead to estimate errors of ±40 per cent or more. Mining dilution (also recovery) is difficult to measure and more difficult to predict. There is no alternative to careful measurement coupled with experience-based adjustment (McCarthy, 2001). For Ore Reserve purposes dilution must be estimated from data obtained from diamond drilling and development. Geotechnical parameters such as RQD, RMR, Q', etc if available, should be modelled during both the resource and reserve estimation stages. Other key variables which require consideration; include the mining method and equipment size, grade variability at the resource boundary, ore geometry and continuity, proposed mining rate and stope design criteria (eg hydraulic radius, rock quality designation and pillar dimensions) and the physical characteristics of the waste material and the ore/waste boundary.

Economic and other uncertainties

Economic inputs into the Ore Reserve estimate are also critical. Such inputs as mining and processing costs (operating and capital); breakeven cut-off grade; minimum mining grade (operational cut-off grade); NSR factors for individual metals; break-even NSR; and depreciation factors for NPV analysis need to be considered. The previous list is self-explanatory and it suffices to say that each parameter has a potential error in its calculation especially when the exploitation will be at some time in the future and only educated guesses can be made as to their likely values at this time. Sensitivity analysis is thus necessary.

The JORC definition of an Ore Reserve includes the following words (JORC, 1999):

> *Appropriate assessments, which may include feasibility studies, have been carried out, and include consideration of, and modification by, realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors.*

In other words, the proper definition of an Ore Reserve depends on a range of factors, which lie beyond the specialist fields of geologists and mining engineers – *economic, marketing, legal, environmental, social and governmental.* Once a feasibility study is reached there will be sufficient documentation on these to allow Ore Reserve definition to proceed. At the production stage these parameters should be well understood and defined.

It is usually well understood that economic, legal and other non-technical factors lend uncertainty to Ore Reserve estimates – and hence to the viability of projects – but there is a tendency to regard the technical data, such as the geological resource model, as precise. However, without considering all of the technical sources of uncertainty in reserve estimates, the presentation of risk-analysis results comparing different economic scenarios is to say the least inadequate in that it does not show the real magnitude of error between realistic worst and best case scenarios. Conditional simulation can be used to fill this confidence reporting gap, as can the recognition and explanation of the expected levels of uncertainty inherent in the Mineral Resource and Ore Reserve classification categories.

MONITORING THE RESERVE – RECONCILIATION STUDIES

Systematic reconciliation studies provide a means of monitoring the quality of the Ore Reserve estimate produced from exploration data for the Feasibility Study and the short term estimate that will include additional grade control data. Studies can be designed to investigate input data (eg sampling quality, database entry, etc), reserve modelling (eg geological interpretation, grade interpolation methodologies, volume estimation, etc) and checking of the final Ore Reserve model (eg comparison of different models, etc). Remember also that the Ore Reserve is quoted as delivered to the mill and does not include the final beneficiation and recovery factors. Reconciliations involve comparisons between the tonnages and grades of any of the following (Gilfilan and Levy, 2001); Mineral Resource estimates; Ore Reserve estimates; grade control estimates (*in situ* or mineable); mined production as delivered to stockpiles and/or the next stage of production; and post-mining production and ore in circuit.

These reconciliations aim to test the internal consistency of the various estimates and to compare the most reliable measures of ore production. Favourable reconciled estimates will lead to increased confidence on forecasts of future production.

Comparison of Ore Reserve estimates against production results is often a much more complicated problem than appears at first sight. Computer-based systems are available to assist in the tracking, reconciliation and depletion associated with this process. Difficulties arise because the data on which such comparisons are based usually comes from a wide variety of sources, and is often obtained using different sampling or estimation methods. Examples of such problems include the following:

1. Ore Reserve estimates of tonnage mined are derived from separate estimates of the volume mined and the *in situ* density. On the other hand, mine and mill estimates are usually based on actual weight measurements of material handled.
2. Mine production for a given period is likely to come from different geographical and geological locations, and sometimes even from outside the reserve. Such material is blended together in plant feed so that it is rarely possible to compare reserve estimates from a single production face with plant results.
3. Stockpiling is normal operating practice, particularly in underground mines, and hence a gap of several days may occur between the time when material is mined and when it is eventually processed.
4. Unplanned dilution will have to be taken into account when comparing planned estimates against production results.
5. Material mined may be handled as several different production streams, as for instance where marginal grade material is stockpiled or treated separately. In other cases, different mineralisation types, requiring different beneficiation techniques may be mined in the same deposit.
6. Incomplete data or different levels of detail in datasets from different sources are other common problems.

DEALING WITH ERRORS IN THE ORE RESERVE ESTIMATE

Statement of assumptions

Every Mineral Resource and Ore Reserve report should include a statement of all the relevant assumptions and methods used to produce it. It should include a clear statement of all sources of error, the likely magnitude of error due to each and the likely impact or significance of each. Such a statement could be in the form of a checklist with specific parameters given an empirical rating (eg a Resource Reliability Rating system; Annels, 1997). This may lead to documents that are less friendly to the project developers, financial experts and mine managers, though in the operational environment would ensure that the entire mining team are aware of the likely problems. It should not be acceptable to report reserves as precise tonnages and grades without any indication of the uncertainties involved.

Methodological solutions: geostatistics

There is no one statistically rigorous way of estimating and reporting the degree of uncertainty in any set of resource and reserve figures. Kriged block grade estimation errors are not useful quantitatively (Henley and Watson, 1998). However, one technique that has potential for modelling uncertainty in grade (and tonnage) estimation is conditional simulation (Thomas *et al*, 1998; Khosrowshahi and Shaw, 2001, Snowden, 2001). The resultant range of likely grade tonnage outcomes can be used to quantify and report the risk in the model at any cut-off grade, or for changes in block size, stope size and/or for different mining periods.

For tonnage estimation, geostatistical methods have been developed for determining optimal deposit boundaries (so-called morphological or categorical kriging) but they have yet to gain wide acceptance or use. The definition of deposit boundaries remains largely the preserve of subjective geological interpretation and the uncertainty in such definitions is thus difficult or impossible to quantify.

Simulation

There is however, a better method for assessing and reporting the potential error in an estimated Mineral Resource – conditional simulation (Snowden, 2001). Rather than simply producing a single set of estimated block grades, this simulates possible detailed sets of possible sample grades that can be re-blocked into meaningful mining block sizes and shapes to represent expected block grades. By carrying out a large number of conditional simulations on the same data set it is then possible to obtain an estimated block grade from the average of all simulated block grades, as well a distribution of likely block grades. The distribution of likely grades allows the uncertainty in the estimate to be reported at any given confidence level. This is clearly superior to the use of the kriging estimation variance. Conditional simulation can now be used for some non-linear geostatistical methods, and it is likely that it will become a standard method for the quantification of estimation uncertainty and risk. The conditional simulation results provide a range of equally-likely grade tonnage curves for the Mineral Resource or Ore Reserve at a given level of sampling information. These results generally better represent the expected Ore Reserve behaviour at a range of cut-off grades than the single grade tonnage curve produced by traditional resource estimation methods.

CONCLUDING COMMENTS

Ore Reserve estimation is not simply a measure of maximum NPV or return on investment but involves other corporate objectives, both quantitative and qualitative. Errors in reserve estimates remain a major source of economic failure in the mining industry. However the processes which contribute to better estimation continue to improve. Moreover, computer based analysis can enable a more precise Ore Reserve to be defined within a given mineralised resource, particularly for complex ores. Methods such as conditional simulation are also available to quantify the confidence in reserve estimates. The appreciation and consideration of this uncertainty is critical for realistic project planning and risk aversion, and the practice of quoting reserve ranges and confidence levels should be encouraged by all involved in the mining industry.

The major source of error in resource/reserve estimates is grade interpolation but this is also arguably the most difficult to improve. Short of cost prohibitive large-scale increases in data density, only attention to all facets of estimating practice can help.

The process of managing an Ore Reserve during exploitation requires effective analysis of operating results (eg reconciliation), attention to changes in the economic environment, frequent, clear communication to all of the consumers of the reserve estimate and recognition that the management and reporting of the Ore Reserve estimate is a fundamental and very important part of a mining company's business.

It must be recognised that two deposits can have the same reported reserves and the same expected mining costs but have a very different financial attractiveness solely as a result of different degrees of certainty inherent in their reserve estimation. It should become standard practice to carry out a full risk analysis – including detailed assessment of all sources of error – as an integral part of reporting any Mineral Resources or Ore Reserves. For resource reports, this will include all technical sources of error; for reserves, it will additionally include economic factors as an integral part of the risk analysis. The aim should be to provide a degree of quantification of the risk in the reported estimate to allow for better decision making by mining project planners, operators and investors.

ACKNOWLEDGEMENTS

The authors would like to thank many individuals who have input into this contribution. Dr Simon Dominy thanks Welsh Gold PLC, Cardiff University, the Royal Society, the Institution of Mining and Metallurgy and the North Queensland Branch of The Australasian Institute of Mining and Metallurgy for funding study leave periods to Australia during 1998 - 2001. Dr Alwyn Annels acknowledges colleagues from SRK Consulting (UK) Ltd, including Dr Mike Armitage, Dr John Arthur, Martin Pittuck and Richard Clayton. Mark Noppé acknowledges colleagues at Snowden Mining Industry Consultants Ltd, including Vivienne Snowden and Ian Glacken. Matt Raine and Lucy Roberts (James Cook University) are thanked for their review of this manuscript.

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