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Errors and Uncertainty in Mineral Resource and Ore Reserve Estimation: The Importance of Getting it Right

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Abstract — Mineral Resources and their subsequent conversion to Ore Reserves are of key importance to mining companies. Their reliable estimation is critical to both the confidence in a feasibility study, and also to the day-to-day operation of a mine. Together with sampling, assaying, geological and other errors introduced during interpretation and estimation, additional errors are likely to be introduced during the application of technical and economic parameters used for conversion of resources to reserves. There is thus a requirement for high-quality interpretation and estimation to be supported by high-quality data. Any company expecting to make sound investment or operational decisions must base this on both relevant and reliable information. An Ore Reserve statement generally contains a single set of grade and tonnage figures without a discussion of the potential inherent errors in these estimates. Some sensitivity studies may be run, but confidence limits are rarely quoted and, if they are, often do not take into account many of the factors that cause uncertainty in the grade and tonnage estimates. Mineral Resource and Ore Reserve estimates thus carry certain errors leading to uncertainty and risk; some of these are unquantifiable for various reasons, for which the operator should be aware. This paper presents a review of the potential sources of error that might occur during a resource estimation program, which are carried through into the reserve estimate. A number of methods are discussed that allow the estimator to be more transparent about the inherent risks in his/her estimate. Emphasis is placed on data quality, and the requirement for strong quality management to be linked to continuous improvement.

Introduction

The reliable estimation of Mineral Resources and 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; Goldsmith, 2002). 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 risks associated with mining are varied and complex, where the dominant source of risk is the orebody itself (Snowden et al., 2002). Mining is different from most businesses because knowledge of the product is essentially based on estimates, which by their very nature include a degree of uncertainty. World commodity prices and exchange rates largely control potential changes in revenue, and consequently the size of the economic mineral inventory. Efficient mining is effectively about managing risk.

The estimation of Mineral Resources underlies the generation of the Ore Reserve. The consideration of errors and uncertainty during estimation is critical to geologists and engineers undertaking these exercises during a feasibility study and 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. Certain errors generated during the feasibility study will often still be present when completing production-based estimates, which will of course have their own errors associated with them. These errors can give the mine operator significant problems when it comes to reconciling the reserve with mine production.

An effective Mineral Resource estimate must integrate a number of different facets, including:

- geological data collection (drilling, mapping, etc.);

- geotechnical data collection;
- sampling and assaying;
- bulk density determination;
- geological interpretation and modelling;
- grade/tonnage estimation;
- validation; and
- resource confidence classification and reporting.

The Ore Reserve estimate depends on the integration of the Mineral Resource estimate with:

- selection of the scale, method and selectivity of mining;
- practical mine planning and scheduling constraints;
- estimation of mining dilution (planned and unplanned) and recovery (extraction and planned and accidental losses);
- rock mechanics and hydrological issues;
- assessment of the amenability to processing and metallurgical recovery;
- prediction of commodity prices/markets;
- project economics and the estimation of breakeven and operational cut-off grades;
- health and safety concerns;
- environmental constraints;
- legal and taxation constraints;
- political stability/sovereign risk; and
- the overall assessment of reserve classification and reporting.

The estimation of Mineral Resources and Ore Reserves is a team effort in which the geologist is arguably the essential component, responsible for the resource model, which underlies the entire process. Finance providers worldwide require transparent and regulated reporting policies to understand the resource/reserve base, and to minimize fraudulent activity. Recent publications such as the TSE/OSC (1999) Mining Standards Task Force Report and the CIM (2002) Estimation Best Practice Guidelines provide recommendations for, among other things, best practice in exploration and estimation, development and mining; quality control for assay laboratories; requirements for technical reports; and establishment of the Qualified Person (QP) concept.

The resource estimate should be managed by a Competent Person (1999 JORC Code — CP is equivalent to the QP). The CP should have relevant experience in the estimation of that style of deposit. The final report should be signed off by the CP who may be held professionally, and potentially legally, liable should a complaint be made in relation to the estimate (Phillips, 2000). Recent times have seen substantial litigation and monetary penalty for poor professional practice (e.g., Equatorial vs Kvaerner; Anon., 2003), and this is likely to continue. It is now recognized that the resource/reserve estimation process involves many different disciplines, thus a number of CPs may have to sign off on the estimate. No matter how good a CP is or how comprehensive the methodology, if the primary data is flawed, so will be the estimate. It is part of the responsibility of the CP(s) to show 'due diligence,' and check data and interpretation quality or recognize where he/she is not sufficiently experienced to make that judgement.

At every stage of a project, quality of data and methodologies should be at the forefront of the technical teams' mind and subject to regular audit. This is a critical part of quality assurance. These audits should synthesize and review the quality of the input data (geological and assay), applicability of modelling techniques used, reliability of grade models and of the various factors used to produce the estimate. Ideally, an independent team should carry this out with no links to the original estimators. This represents an important activity, giving confidence that the final Ore Reserve would stand up to a due diligence review and actual production. This audit procedure is often a luxury in a production and reconciliation environment, often to the detriment of the operation that should be striving for optimal reserve utilization.

It should be noted that reporting a resource and reserve estimate in compliance with one of the reporting codes does not necessarily mean that it is a quality estimate. Reporting within the framework of a certain code means that the process is clear and transparent, and that the figures have been reported in a prescribed manner. Reporting codes such as JORC are effectively only a minimum standard for reporting, the actual business of estimating the resource/reserve is up to the CP(s).

This paper reviews the common errors and uncertainties that may be encountered in resource and reserve estimates, and that may need to be allowed for during mine planning and production. It suggests a number of methods by which resource and reserve uncertainty, and hence risk, can be better stated. Emphasis is placed on data quality, and the requirement for strong quality management to be linked to continuous improvement. The text draws on the reporting experiences of the authors, principally within Eastern and Western Europe, the CIS, and Australasia, though the discussions are relevant to all jurisdictions worldwide.

Part 1 — General Background Issues

Mineral Resource and Ore Reserve Classifications

Current classifications of Mineral Resources and Ore Reserves are based on geological assurance (e.g., characteristics of the orebody, especially geological and grade continuity), data quality (e.g., sampling and assay quality, etc.), and technical feasibility and economic viability under present cost and price structures (Stephenson, 2000; Stephenson and Stoker, 2001). Though the latter two factors can be assessed adequately, geological assurance often relies heavily on subjective classifications based on, for example, sampling density in relation to the likely continuity and nature of the mineralization. The 1999 JORC code states that a Measured Mineral Resource, as outlined in Figure 1, is:

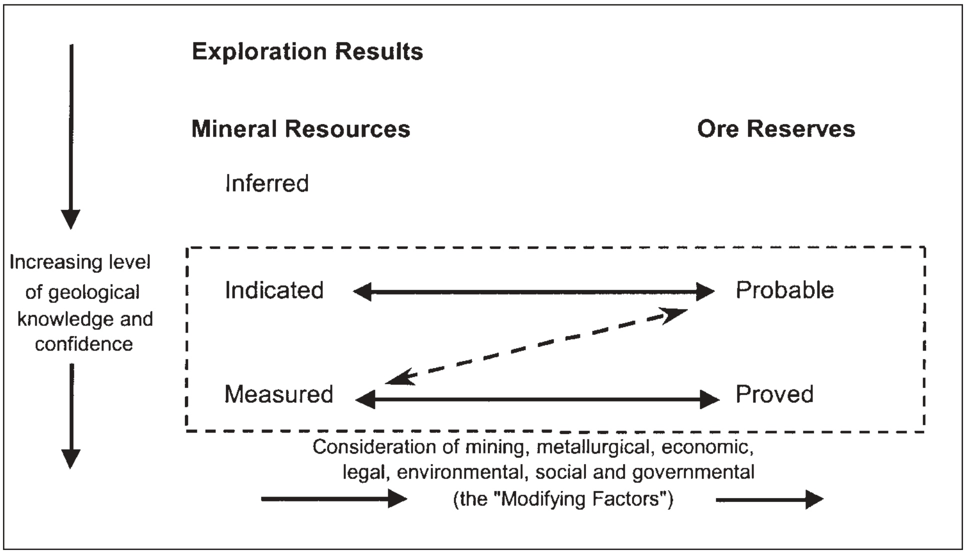

Fig. 1. General relationship between exploration results, Mineral Resources and Ore Reserves (JORC).

"*...that part of a Mineral Resource for which tonnage, densities, shape, physical characteristics, grade and mineral content can be estimated with a high level of confidence. It is based on detailed and reliable exploration, sampling and testing information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes. The locations are spaced closely enough to confirm geological and/or grade continuity.*"

It is surprising that for the highest resource category, continuity for geological and/or grade continuity is required. Overall, the definitions of Inferred and Indicated Resources in the 1999 JORC code are confusing. Both require the assumed continuity of geological and/or grade, despite the fact that the data density for the Indicated Resource should be considerably denser than that for the Inferred Resource. Proper resolution of both grade and geology is surely a critical requirement for the Measured Resource (hence Proved Reserve). It is likely that this anomaly will be addressed in the proposed 2004 JORC code revision.

Various workers have attempted to provide guidelines for the classification of resources and reserves based upon the perceived precision of the estimates (e.g., Vallée, 1992). These are generally intended to be qualitative or intuitive in nature, based on consideration of all the factors that might impact on confidence. In particular, they are not directly related measurements of sample configuration or grade computational efficiency such as kriging variance (Diehl and David, 1982), kriging efficiency (Krige, 1996) or the results of conditional simulation studies (Khosrowshahi and Shaw, 2001; Snowden et al., 2002). Table 1 presents examples of precision ranges, which may give appropriate levels of uncertainty for classification.

These guideline ranges should take into account the entire resource process (i.e., include allowances for sampling, etc.), though in practice they are generally related to the resource estimation and classification process only. The precision of estimation relates to our ability to model the orebody both geologically and numerically, and to whether the estimation procedure is suitable and efficacious. However well we apply estimation techniques, we are still faced with the problem that an apparently high confidence in estimation techniques can be undermined by serious errors in the data used.

For example, a high-nugget effect coarse-gold bearing deposit will require special sampling considerations to account for the inherent problems in sample preparation and assaying (e.g., poor reduction of gold particle size, sample heterogeneity, etc.), and grade estimation (e.g., mixed populations, skewed distribution, etc.; Dominy et al., 2000a, 2000b, 2003a, 2003b). These errors are often not addressed by the project team and CP, and may not be adequately accounted for during estimation and reporting.

In the future, it is expected that reporting codes will require fuller discussion of the relative accuracy/confidence in the estimate. It is likely that specific levels of confidence may be expected (e.g., Table 1).

Table 1. Potential precision levels at the 80% or 90% Confidence Levels for Mineral Resource and Ore Reserve estimates, for example, over a 12 month production period

Mineral Resource	**Precision: Developed/Undeveloped**
Measured	±5-10% / ± 10-15%
Indicated	±15-25% / ± 25-35%
Inferred	±35-100%

Note: Levels of precision may change depending upon the type of estimate, and hence data density. For example, a drilled-out Proved Ore Reserve block(s) could lie within a 10% to 15% precision range, whereas, if the same block(s) was fully developed, 5% to 10% may be likely. Deposit type will have a very clear influence on attainable resource and precision levels. For example, a high nugget-effect gold vein deposit with low grade and geological continuities may never be able to reach the Measured/Proved categories because of grade estimation uncertainties, even after underground development.

Quality Assurance and Quality Control

The issue of quality assurance (QA) and quality control (QC) during exploration, evaluation and exploitation has been at the forefront of industry perceptions since the Bre-X affair in the late 1990s. Quality assurance consists of the overall policy established to achieve the orientation and objectives of an organization regarding quality (Vallée, 1998a). Quality control designates the operational methods, and aims used to meet the quality objectives (Vallée, 1998a). The four key steps of QC are: setting standards, appraising conformance, acting when necessary, and planning for improvements.

The term "best practice" is commonly used during resource estimation to hint at some form of effectiveness of procedures. However, statements such as "this resource was estimated using industry best practice" are unclear, unless the actual practices are fully documented and verified. Abbott (2003) gives three reasons why the term is often misleading. Firstly, "best practice" is not always best; secondly, with evolving technology, the "best practice" of today is not that of tomorrow; and finally, to potentially hold up during legal proceedings, the "best practice" needs to be published (e.g., in a formal handbook). We should perhaps be striving for "adequate professional practice" as a minimum requirement (Vallée, 2000).

Quality is a critical issue at all stages of a minerals project (Nappé, 2004). For example, QA/QC of analytical and test data, and the corroboration of geological data within the resource/reserve estimation process must now be considered mandatory. Indeed the Canadian National Instrument 43-101 requires mandatory QA/QC programs (CSA, 2001). The JORC Code does not prescribe QA/QC programs but, for example, QA/QC for sampling/assaying is implicit in its Table 1 (JORC, 1999). Periodic audits (part of ISO 9001) should assess the quality of the input data (geological, assay, etc.), applicability of modelling techniques used, reliability of grade models and of the various factors used to produce the estimate. An independent team should carry this out with no links to the original estimators. This represents a vital activity, giving confidence that the reserve will ultimately stand up to a due diligence review. The Mining Standards Task Force Report (TSE/OSC, 1999) set a target of continuous improvement and constant vigilance. Emphasis is placed on the role of the QP (e.g., CP), and the need for management to commit to QA/QC.

The consequences of poor quality are obvious, and could include, for example, investor disaffection, inappropriate planned engineering and financial requirements, poorly supported decisions, upward revision of budgets, cost overruns, late completions, lower mine production, and project failure and bankruptcy (Vallée, 1998a). The important role of QA/QC systems throughout all facets of the life of a mining project cannot be over-stressed (Vallée, 2000). Many mining companies now employ continuous business improvement models to facilitate continuous quality improvement (DeVitry, 2002).

Continuity — A Critical Concept

The Importance and Definitions of Continuity

Continuity is a topic of great concern in the definition of Mineral Resources and Ore Reserves within the JORC and other reporting code frameworks (Dominy et al., 2003a). For example, the 1999 JORC Code defines the confirmation of continuity for Measured Resources, through to assumed continuity for Inferred Resources.

The quality of a mineral resource estimate depends on how well geological and grade continuities are known, on top of the quality of the actual data used. They determine the types of boundaries between lithological/mineralized units, and provide an understanding of the different grade distributions within geological domains (Dominy et al., 2003b). Continuity explains long- and short-range variability, provides reasons for the occurrence of spatial directions and anisotropies, and is the basis for understanding the behavior of grade within domains. In general, two types of continuity are defined in the framework of estimation (Sinclair and Vallée, 1994; Dominy et al., 2003a):

1. geological continuity — the geometric continuity of the geological structure(s) or zone(s) hosting mineralization (e.g., orebody thickness and up-/down-dip continuation); and
2. grade continuity — the continuity of grade that exists within a specific geological zone, sometimes called the value continuity.

It is critical to note that grade and geological continuity are scale-sensitive characteristics. Using a gold vein as an example, the large-scale geological continuity of a structure may be great (1000's m), whereas, the continuity of a gold-carrying vein within a larger structure may be small (10's m). Because the gold is hosted in a small-scale vein, there is very poor gross grade continuity, but within those veins grade continuity could be very good. For this reason it is suggested that continuity be discussed at global (large — 1000's to 100's m) and local (small — 10's m) scales.

Geological and grade continuity assessments are an integral part of resource modelling. Geological continuity has important implications for the estimation of tonnage. It is particularly important to remember that geological continuity is a 3D feature. An orebody may have good vertical and horizontal global continuity, however, if its width varies both erratically and significantly on a local scale, the tonnage estimate will be poor if the drilling density is insufficient to pickup such variations. The implications of grade continuity for grade estimation are obvious.

Continuity and Resource/Reserve Categorization

Table 2 shows generalized continuity criteria for resource and reserve categories that will vary from deposit to deposit. It is important to note that the Inferred Resource is based upon apparent (global) geological continuity in

Table 2. Generalized continuity criteria for Mineral Resource and Ore Reserve categories

Resource/Reserve Class	Data Density	Geological Continuity	Grade Continuity
Inferred Mineral Resource	• Based on geological information, and widely spaced and potentially isolated data.	• Global continuity assumed (in either 2D or 3D), but not established. • Local continuity issues unresolved. Local continuity potentially resolved along, but not between drill holes. • Semi-quantitative estimate of global tonnage with high error margin.	• No continuity established except along axes of drill holes. • Approximate nature of orezone(s) defined (assumed), but not established. • Semi-quantitative estimate of global grade with high error margin.
Indicated Mineral Resource (Probable Ore Reserve)	• Based on geological information, and moderately spaced data.	• Global continuity partly realized in 3D. • Local continuity issues potentially partly resolved. Local continuity resolved along drill holes. • Global/local estimate of tonnage with a medium margin of error.	• Local continuity may be partly established. Local continuity resolved along drill holes. • Some resolution of orezone(s) grade distribution and geometry. • Quantitative estimate of global/local grade with a medium margin or error.
Measured Mineral Resource (Proved Ore Reserve)	• Based on geological information and close-spaced data. • May also involve underground development, and bulk sampling/trial mining.	• Global continuity realized in 3D. • Local continuity resolved. • Global/local estimate of tonnage with a low margin of error.	• Local continuity well established. • Detailed resolution of orezone(s) grade distribution and geometry. • Quantitative estimate of grade and local estimate, with low margin of error.

Note: The content of this table provides some general characteristics for guidance only. It is important that the CP treats each deposit on an individual basis. It should be noted that various other parameters should also be considered when reporting Mineral Resources and Ore Reserves (e.g., drilling techniques, sample recovery, assay quality etc.), and not just continuity. The reader is referred to Table 1 of the JORC Code for more detail on some of the relevant issues (JORC, 1999).

two or three dimensions, supported by samples that are few and widely spaced. It is unlikely to be possible to delimit the ore zone within any level of certainty. Any estimate of grade and tonnage is likely to be semi-quantitative and with a high margin of error. At the other end of the spectrum, fully realized global continuity and establishment of local continuity characterize the Measured Resource. However, to achieve this, it is likely that close-spaced drilling and underground development will be required, depending upon deposit type.

Types of Exploration and Mining Project Appraisals

Three types of project appraisals are recognized within the mining industry. These describe studies of increasing detail and can be applied to any component of a project. Table 3 describes the three types of study and the levels of detail for certain parameters that may be required for a particular deposit. When considering resource/reserve estimation programs, it is important to understand the level of

Table 3. Types of project appraisal studies and data for an underground mesothermal shear-hosted gold deposit showing good geological continuity (over 50 m to 100 m scale) and a moderate-high nugget-effect (e.g., ~60%)

	Scoping/Conceptual Study	Pre-Feasibility/Preliminary Study	Feasibility/Definitive Study
Data density/spacing	Relatively wide spaced (50 m to 70 m) HQ/NQ surface drill holes	Closer-spaced (25 m to 40 m), further HQ or NQ surface and some underground drill holes, and minor underground on-lode development	Close spaced underground drilling (15 m to 25 m), and on-lode underground development
Continuity resolution	General assumptions about gross geological continuity. Little or no resolution of grade continuity	Better understanding of geological continuity, and some resolution of grade continuity	Resolution of both grade and geological continuity at the local scale
Resource definition	Global — Inferred	Global — Indicated and Inferred	Some local estimates — Measured and Indicated, with Inferred
Reserve definition	Not defined	Proved	Proved and Probable
Mine design	Very conceptual	Conceptual	Detailed
Mine scheduling	None	Conceptual	Detailed
Process design and testing	Some	Yes	Detailed
Environmental Impact Assessment (EIA)	Some preliminary studies	Yes	Essential
Economic analysis (DCF)	Not meaningful	Preliminary	Yes — full investigation of IRR and NPV
Operating cost estimate	Assumed	Estimated	Calculated
Capital cost estimate	Assumed	Estimated	Calculated

Note: The levels of drilling and underground development will change from deposit to deposit depending upon geological characteristics, etc. For example, a low continuity/high-nugget gold deposit will require substantial underground development at both the pre- and final-feasibility stages. QA/QC programs are required at all stages of mineral deposit appraisal.

study involved (e.g., scoping, pre-feasibility and final feasibility studies) and the expectation of such a study (Vallée, 2000).

The scoping study (conceptual study) is essentially an order of magnitude study based on a resource estimate that is likely to be dominated by Inferred and Indicated Resources. The drill/sample spacing will be wide, and is only likely to resolve continuity issues over a global scale.

The pre-feasibility study (preliminary study) requires more accurate determination of resources based upon further closer spaced drilling, resulting in the definition of Indicated and Measured Resources (depending on the style of mineralization). Continuity will be resolved on the global scale, and on the local scale for Measured Resources. Some Inferred Resources are likely to be still present, though these should not be included in calculations that involve economic forecasts. Consideration is made of engineering aspects such as mine design, process testing and estimates of capital and operating costs.

In the feasibility study (definitive study), a full and detailed investigation is made of all aspects of the operation. The term feasibility study generally describes a study that is appropriate to make a decision on a project requiring design, plans and estimates, and cash flow forecasts (Vallée, 2000). In practice, the scope of an actual study is variable, so that a 'bankable feasibility study' is specified when due diligence is required. Vallée (2000) notes that there is some varied opinion in what level of confidence should be applied for a feasibility study, and in some cases is set by the project management/owner. This situation is clearly problematic and should perhaps signal more rigorous requirements.

During a feasibility study, the level of geological information should be based on 'close-spaced' drilling and potentially underground development/trial pit mining to demonstrate local geological/grade continuity. If the sample spacing and quality is appropriate, this will result in the definition of Measured and Indicated Resources, and Proved and Probable Reserves. Inferred Resources may still be defined at some edges or depth extents of the mineralization, though they should not be used for any economic viability calculations. Poorly expedited feasibility studies are the common cause of frequent cost overruns and low average mining industry returns compared to other industrial sectors (Vallée, 2000; Horn, 2002; McCarthy, 2003). Any feasibility study supporting a sizeable investment decision should be based on complete delineation, estimation, testing, planning and design.

Types of Resource and Reserve Estimate

Different types and levels of confidence 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 produced to varying levels of sophistication and detail.

Scoping and Pre-feasibility Study

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 a global resource estimate and an estimate of the likely grade-tonnage curve within a deposit. The outlines of the deposit are generally defined by geological and/or grade boundaries from within which representative samples have been taken. Insufficient data are generally available at this stage to allow for accurate local block grade estimation.

The grade tonnage curve generated from this block data is likely to be smoother and less selective than in reality if grades are estimated using an averaging technique (e.g., inverse distance weighting or kriging). This means that such a grade tonnage curve will represent the selectivity of blocks significantly larger than the likely selective mining unit (SMU) size and will therefore be over-diluted. Polygonal estimates, on the other hand, may be too selective and report a higher grade and lower tonnage at a cut-off grade than may be realistically achievable.

Recognition of these issues is essential so that alternative, often indirect geostatistical methods can be applied for determining the likely grade tonnage curve. The grade-tonnage curve must be corrected to obtain the grade-tonnage curve of the SMUs that will be possible once grade control-spaced data are available during production (for example, by applying the affine or indirect lognormal correction, or uniform conditioning). For this correction to be undertaken correctly, geostatistical methods must be used, as conventional methods do not have this capability. The effects of mining loss, dilution and extraction must also be taken into consideration.

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 likely to be similar to that for blocks of size roughly equal to the drill spacing, whereas, the size of the selective mining unit is normally much smaller. Once again, the grade-tonnage curve and selectivity must be corrected to obtain a more realistic representation of the grade-tonnage curve for SMU-sized blocks.

Final Feasibility Study

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 and must be supported by enough data to resolve small-scale geological and grade features. Once again, the local block grade estimates are likely to provide grade tonnage relationships for blocks larger than the planned SMU size. If adequate data are 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.

Suitable geostatistical methods such as indicator kriging or uniform conditioning can be used to make an initial estimate of the recoverable reserve in each resource block during global resource estimation. Conditional simulation can be used to better assess the expected local reserves by interrogating the simulated sample data to report the likely grade-tonnage curves for a selected SMU size. The multiple simulations will provide a spread of likely grade-tonnage curves, which can be used to define the envelope of uncertainty in the estimated results (Snowden et al., 2002).

Production 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. At this stage, more detailed sampling information will be available to undertake the estimate into smaller blocks. The closer spaced samples and improved geological control provides greater confidence in the estimate of SMU grades for final block selection decisions. Selection can also be aided by applying probabilistic estimates and conditional simulation that provide the probability of a block exceeding the cut-off grade constraints. Block estimates need to be assessed within practical mining shapes with appropriate allowances for mining loss and dilution.

Significance of Errors in Estimates

Industry Performance

Burmeister (1988) reviewed 35 Australian gold operations, which were started in the period 1984-87, 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 (1991) examined Canadian gold mining operations and found only a few had lived up to original expectations. The two reasons most commonly identified were related to poor grade estimation and inadequate assessment of dilution and mining losses.

In a recent unpublished study, Dominy (2002a) reviewed the resource/reserve performance of small- to medium-sized Australian gold operations. It was found that most problems were related to geological, sampling and grade estimation issues, and that the majority of operations were producing more tonnes (up to +15%) and less grade (up to -55%).

McCarthy (2003) reports results from a survey of 105 examples identifying common issues arising from inadequacies in the feasibility study. The key problems identified were with geotechnics (9%), metallurgical testing (15%), resource/reserve estimation (17%), and mine design and scheduling (32%). McCarthy estimates that issues directly linked to geology inputs across all problem areas actually account for some 66%.

Agarwal et al. (1984) investigated a number of base metal mining projects, and concluded that the most common issues were related to start-up delays and poor performance during the first few years' production. Specific problems cited were: high orebody heterogeneity (e.g., not enough delineation drilling); inadequate sampling (e.g., requirement for bulk samples); and process issues (e.g., need for better plant scale-up and design).

From the geological standpoint, King et al. (1982) stated "it is the geological factor that has impressed itself on us more and more as being the key deficiency where serious weaknesses in Ore Reserve estimations have appeared."

Common Errors Leading to Resource/Reserve Problems

Specific Example

Table 4 shows the effects of an erroneous Ore Reserve estimate produced at the feasibility study for an underground gold mine. This is a real example where after 12 months of production a potential buyer undertook a full audit prior to purchase. The impact of the revised estimate was negative, showing a large reduction in reserve grade and tonnage, and hence contained ounces. At the same time, much of the remaining resource was downgraded to the Inferred Resource category.

This example demonstrates the need for QA/QC programs during a feasibility study (and at other project stages) which were not present in this case. The key points for concern were:

- poor sample quality in some instances (poor core recovery);
- inappropriate sample preparation protocols in a coarse gold environment;

Table 4. Comparison between the original and revised resource/reserve estimates for an underground moderate-nugget effect narrow-vein gold deposit

Mineral Resource	Tonnage/Grade	Ore Reserve	Tonnage/Grade
Original feasibility study estimate (at a breakeven cut-off grade 4.5 g/t Au)			
Measured	170 000 @ 11.9 g/t Au	Proved	150 000 @ 9.8 g/t Au
Indicated	130 000 @ 15.4 g/t Au	Probable	100 000 @ 12.3 g/t Au
Inferred	400 000 @ 9.8 g/t Au	Possible	230 000 @ 8.1 g/t Au
Total	700 000 @ 11.6 g/t Au	Total	480 000 @ 9.5 g/t Au
Contained oz	255 500	Contained oz	147 000
Revised estimate (at a breakeven cut-off grade 6.1 g/t Au)			
Measured	75 000 @ 8.7 g/t Au	Proved	55 000 @ 6.3 g/t Au
Indicated	95 000 @ 8.9 g/t Au	Probable	70 000 @ 6.4 g/t Au
Inferred	250 000 @ 6.5 g/t Au	-	-
Total	420 000 @ 7.4 g/t Au	Total	125 000 @ 6.3 g/t Au
Contained oz	99 900	Contained oz	25 500

Parameter	Mineral Resource	Ore Reserve
Differences between the original feasibility estimate and the revised estimate		
Tonnes	-40%	-74%
Grade	-36%	-34%
Contained gold	-61%	-83%

Note: The reserves are included in the resource base.

- low data density in many areas;
- problems with perceived geological and grade continuity; and
- problems with the estimation method used (inappropriate polygonal method with a high top-cut).

For the reserve estimates there were problems with:

- under-estimation of both planned and additional dilution;
- over-estimation of extraction for the chosen mining method; and
- under-estimation of the breakeven cut-off grade.

The project was subsequently abandoned with substantial losses to the operator.

General Issues Contributing to Resource/Reserve Issues

There are five principal geological reasons for incorrect resource estimates:

1. poor sample and assay quality data;
2. a lack of detailed mine geology and fundamental understanding of the deposit;
3. poor interpretation of grade distribution characteristics;
4. poor understanding and application of computer-assisted estimation techniques; and
5. the failure to recognize affect of selectivity and the change of support or volume-variance effect, namely, that mining needs to be controlled on the grades of large tonnage blocks and not small-volume samples.

Across the board, the downgrading of resource/reserve estimates as a result of feasibility and operational due diligence studies/audits are usually related to one or more of the following issues:

- drill hole orientation with respect to the ore zone/dominant mineralization orientation;
- inadequate primary sample, sub-sample or pulp volumes;
- assay quality, accuracy and repeatability (precision and bias);
- poor correlation between analyses of duplicate field splits;
- poor or variable core sample recovery;
- highly variable sample recovery;
- biased sampling techniques;
- presence of coarse gold;
- inappropriate and/or mixed drilling techniques (e.g., wet RC);
- poor correlation between analyses from twinned holes (e.g., RC vs RC or RC vs DDH);
- down-hole contamination/smearing;
- lack of down-hole orientation surveys in long holes;
- combination of sample data which are incompatible statistically or from the point of view of sample quantity and quality;
- problems with the compositing of raw sample data;
- poorly understood or demonstrated geological and/or grade continuity;
- inappropriate geological interpretation and geological modelling techniques;
- inappropriate resource estimation techniques;
- inadequate determination of bulk density of ore and waste;
- poor dilution and loss assessment;
- impractical mine planning assumptions (block continuity and practical mining shapes); and
- metallurgical recovery issues.

Consequences of Errors

The economic consequences of errors and the lack of understanding of the effects of uncertainty in the reserve estimates can potentially be disastrous. A 10% error in grade estimation is not uncommon, and is generally regarded as acceptable for an underground operation (for example, over a one-year period). However in some cases, production/Ore

Reserve reconciliation will show errors of ±50% to 80%. When it is considered that even for a good operation production costs are at least 50% to 75% of the mine site revenue, it can be seen that even a 10% decrease in grade can translate to a 20% to 40% 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 amortization and depreciation charges. It can also render a financially stretched project non-viable.

A second consequence of serious error in an original estimate is the need to produce an updated estimate based on new interpretations or data, which may result in 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.

Part 2 — Uncertainty in Mineral Resources and Ore Reserves

Discussion of Uncertainty in Resource/Reserve Estimates

Mineral Resource and Ore Reserve reports generally contain a single set of grade and tonnage figures without reference to, or quantification of, the potential inherent uncertainty in these estimates. In this case, the emphasis is on the inherent inability to estimate the figures accurately from the available information, rather than some systematic error or bias in the 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. The key sources of uncertainty are discussed below, though the list is by no means exhaustive.

Tonnage Estimation Uncertainty

Errors in tonnage estimates are often poorly considered and rarely quantified. Estimates are often quoted to five or six significant figures implying a high level of accuracy that is not there. The key components of a tonnage estimate are surface area and thickness leading to volume, and bulk density.

Definition of the Deposit Boundaries — Volume Issues

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 or *en echelon* arranged pods of mineralization. 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.

One particular issue in volume determination is the accurate location of drill intersections (e.g., X,Y,Z co-ordinates). It should be established if the drill hole collars were surveyed and, if so, whether they were internally surveyed and at what interval. If a deviation of 1° per 50 m occurs in a hole, which has been assumed to be straight, then after 500 m such a hole could be displaced by up to 50 m from its anticipated location. Prenn (1992) records that deep RC holes are not always surveyed and that considerable deviation is possible. This is further supported by Ayris (1990) who reports that a 50 m RC hole deviated 12 m from its target. This could seriously affect the quality of boundary delineation, and therefore of volume modelling.

Bulk Density

Bulk density is defined as the density of material that includes natural voids. It can either be reported as the dry bulk density rather than the in situ wet bulk density that includes natural water content (Lipton, 1997). The water content should be determined separately and applied as required to the as delivered bulked material tonnage.

The correct determination and reporting of bulk density for resource estimation is often overlooked. The test method used is generally suitable for determining the density of the small sample, but it may not be indicative of the physical characteristics of the larger material mass. 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 (e.g., sphalerite-galena-barite ratios). 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.

Although it is a requirement for project funding that any resource estimate should include the basis for the selection of the bulk density, it is sometimes neglected. Few, if any, orebodies are homogeneous and just as grades vary, so does the bulk density of ore and waste. Ignoring variations may result in the tonnage and metal content of heavier than average rock being under-estimated, or conversely, over-estimation of lighter than average zones (Dadson, 1968; Parrish, 1993).

Establishing the bulk density of a deposit involves the same problems encountered in grade estimation. Bulk density varies with rock type, degree of fracturing, and weathering and porosity, as well as the intensity of mineralization. Within a gold-sulfide vein, bulk density values may vary from 2 to 5 t/m^3 depending on these factors. Because of these variations, the application of an average bulk density in most deposits is unacceptable and it is important to undertake a program of measurements on core and rock samples (Parrish, 1993; Lipton, 1997, 2000). In these cases, dry bulk density values should be modelled along with grade during resource estimation. Density weighting of the grades during sample composting and average grade determination may also be required.

Interpretation Uncertainty

In the estimation of orebody volume and hence tonnage, it is necessary to make a decision on what parts of the resource should be considered as Measured and Indicated Mineral Resources and what parts are likely to be outside of 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 CP. Many different approaches have been adopted, such as judgement based on experience, relating the resource tonnage to defined distances between drill holes, using threshold values of geostatistical estimation variance, or conditional simulation approaches, but there remains no generally accepted standard method of defining the boundary for Measured and Indicated Resources, or Proved and Probable Reserves. Volume errors may also be introduced by incorrect interpolation of ore-waste boundaries at deposit margins, and between areas assigned to each category of resource confidence.

Grade Determination Uncertainty

The estimation of grades has been recognized as challenging for many years. Assuming a suitable modelling approach has been selected, two main sources of error in grade estimation remain: (1) sampling error and (2) estimation error.

Sampling Selection Error

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 raw data. It is unfortunate that this source of error is virtually ignored in many reserve estimates, although the random errors contribute to the nugget variance modelled and reported in geostatistical methods. The total error in a sample assay result is a composite of a number of different sources of error (sampling representativity, sample bias, sample preparation, analytical error, coding and transcription errors).

The sampling selection error is of particular significance in low-grade concentration materials such as gold and diamond deposits and other minerals or grades that have a highly skewed distribution and/or a large difference in mineral density or particle size (Dominy et al., 2000b, 2004a). Each source of error results in effective smearing 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 mask the expected variability of a deposit causing significant problems in subsequent selective mining and reconciliation. An artificially high nugget effect will imply that the grade is less continuous and less selective than in reality. Some of the sources of error that might be incurred during the sampling phase are listed below:

- unsuitable drilling method;
- inappropriate drill hole inclination relative to orebody dip;
- variable diameter/volume of core or sample;
- poor core/sample recovery and quality;
- contamination;
- blocking errors;
- selection criteria for sample length;
- poor quality sampling practice and/or sampling bias;
- poor sample preparation protocols;
- ability of sample to represent mineralization;
- sample delineation and selection problems; and
- core handling and checking (including tampering with and removal of the core).

The drilling density might also be inadequate in relation to the geostatistical zones of influence or grade continuity of the mineralization, the physical continuity of ore pods and the frequency of structural elements dislocating or disturbing the continuity or uniformity of the mineralized body.

The core size/sample volume may be inadequate given the type of mineralization, while the ground conditions, drilling technique, or intersection angle to discontinuities in the rock mass may all result in poor recovery. Sidewall abrasion and collapse (hence >100% recovery) may introduce contamination if the drilling method is not matched to the ground conditions or if the sample recovery method is unsuitable. Tomich (1992) and Prenn (1992) stress the problems of contamination incurred by the use of RC drilling below the water table and during the use of open-hole RAB drilling. Prenn (1992) also notes that RC recovery can reach as low as 1% and that >80% recovery can be regarded as satisfactory. These and other problems related to the use of RC drilling are reported in Goodz and Frith (1993) and Goodz and D'Astoli (1997).

During drill core sampling, errors can be induced by the selection of unsuitable sample intervals in relation to changes in mineralogy, host rock lithology and metallurgy. Similarly, errors in the estimation of true sample length due to measurement of intersection angles and depths, and problems related to core recovery are possible. The latter is particularly serious, as there is no satisfactory way to allow for the fact that nothing is known about the grade of the portion of the core that has been lost (Annels and Dominy, 2003). High core losses throughout an orebody can seriously undermine the confidence in an Ore Reserve estimate. In most cases, this is totally ignored and the assumption made that the grade of the missing sample is the same as that recovered. The increased risk may therefore not be reflected in the resource and reserve classification (Annels and Dominy, 2003).

Intersection angles can either be directly measured or interpreted from borehole correlations. Errors in these angles will result in incorrect thickness estimates for potential ore zones. A very low intersection angle of the hole to the mineralized zone can also introduce an error in domain delineation as the intersection points of the hangingwall and the footwall will be displaced so far apart down the dip from one another that considerable grade or mineralogical change could have occurred in this distance. In this case, the samples are not necessarily representative of the changes that have occurred normal to the median plane of the orebody at one point in 3D space.

Blocking and delineation errors may also relate to the drillers' imprecise estimates of the depth ranges from which samples have been obtained (poor resolution due to lag time in the case of open hole percussive drilling) or to inaccurate depth measurement from rod stick-up. Errors can also be incurred through displacement of depth blocks or the core itself during handling and transport.

Changes in core or hole diameter may mean that the sample support is no longer constant in the data set. This may occur in response to insertion of casing, or between adjacent drill holes, or between different drilling campaigns. This is not always taken into account and introduces the problems of mixing different sample types and supports and highlights the potential problem associated with the volume-variance effect (larger volume introduces a lower sample grade variance). Finally, the checking of core prior to assaying needs to be undertaken to ensure that core sticks are in the correct order and have not been either inverted and/or misplaced in the core box.

Sample Preparation and Assaying Error

The potential sources of error during the preparation and analytical phase include: sample reduction, crushing and pulping; contamination; salting; analytical method and procedures; data transcription; and experience of laboratory technician.

Serious errors can be introduced during sample reduction (crushing, pulping, splitting) and homogenization, especially in the presence of coarse gold (Dominy et al., 2000b). Sample reduction relates to the method by which samples are reduced in mass for further preparation and analysis. Inadequate jaw crushing prior to sample splitting is a common source of error at this stage. At each stage in the sample reduction and splitting process, errors can be introduced, not only because of the selection of an inadequate sample volume in respect to grain size and abundance of the valuable mineral, but also because of contamination and a poorly homogenized sample pile which may result in non-representative sub-samples. Further errors may also be introduced by poor analytical procedures and data transcription.

Many of these errors can be minimized through good work practice (e.g., QA/QC), correct equipment, suitable physical sample selection (representative sampling) and handling (dealing with segregation). Sample size and reduction procedure errors relate to the inherent heterogeneity of the mineralization and these errors can be assessed by the application of Gy's sampling theory (Gy, 1982). The importance of well-designed and implemented sampling programs is stressed by numerous authors (Sawyer, 1992; Long, 1998; Shaw et al., 1998; Sketchley, 1998; Vallée, 1998a, 1998b; Hellman, 1999).

Sampling and the Nugget Effect

Nugget effect is a quantitative geostatistical term describing the level of variability between samples at very small separation distances. Those systems with a high-nugget effect are the most challenging of mineralization types to evaluate (Dominy et al., 2000a, 2000b, 2003a). It can be shown that a high nugget effect can be related to poor sampling practice (Dominy, 2004a). The randomness introduced makes prediction of unsampled locations difficult. As a result, understanding and reducing the nugget effect has significant economic importance. In practical terms, ensuring rigorous QA/QC programs during sample collection, preparation and analysis can reduce the 'sampling' component of the nugget effect (Dominy, 2004a). The 'geological' component of the nugget effect can be understood through careful interpretation of geology and grade distribution, and by selecting the optimum sample size and density.

Estimation Uncertainty

Errors during the resource estimate are those that are related to database problems, geological modelling, and the estimation method used.

Database Construction Errors

The resource database is established by the collection, recording, storing and processing of data. Its validation as part of a QA/QC program is essential. Numerous errors can occur during database construction, both of the raw data and of the validated and 'accepted' data; these can include:

- data transcription;
- database compilation;

- magnetic versus true north errors;
- co-ordinate transformations;
- downhole survey errors;
- missing intervals and/or inconsistent downhole stratigraphy;
- inconsistent lithology coding;
- treatment of absent and below-detection limit values;
- significant reporting figures and scales (e.g., percentage and ppm);
- selection of 'acceptable' values from repeat assays;
- merging of lithology and assay intervals;
- drill hole unrolling and de-surveying;
- data subdivision;
- grade compositing;
- bulk density determination;
- grade weighting;
- data correction; and
- inclusion of incompatible sample data sets.

Particular attention needs to be channelled into database verification; drill hole de-surveying; domaining, and grade compositing (Long, 1998). It is also essential that all relevant information be recorded, particularly that relating to sample quality and recovery (Annels and Dominy, 2003).

Geological Modelling Error

Introduction

The treatment and subsequent interpretation of geological data forms the basis of the Mineral Resource and Ore Reserve estimate. Information that needs to be determined to assess the impact of the geology on the modelling of the mineralized zone is:

- grade continuity/variability;
- geological continuity/variability;
- effects of faulting 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 these errors is never so important as during the estimation of local reserves prior to or during production. As discussed previously, issues related to grade and geological continuity are closely linked to the spacing and density of drill holes. The poor resolution of continuity and assumptions about it are a common source of error and thus uncertainty in the resource estimate.

Drill Spacing/Sample Density — Resolving Continuity and Geometry

The issue of drill/sample spacing is an important one. The ultimate question is what is the optimum spacing required to do the job? In reality, it is related to the level of risk that management is prepared to accept in relation to potential cost. However, it is more appropriate that we consider what sample density will resolve continuity and sampling requirement for the study in hand (e.g., scoping vs prefeasibility vs full feasibility study). There have been many instances where management have simply decided to spend a certain amount of money on drilling for a feasibility study. However, this level of data has been wholly inappropriate for the deposit and the expiation of a feasibility study (e.g., definition of Probable and Proved Reserves). The requirements of the deposit must guide the resource/reserve definition program and not the bank balance. There is no point expecting a 50 m by 50 m pattern to define Ore Reserves in a complex shear-zone gold deposit.

Where the drill spacing does not resolve the geology and geometry (and hence continuity) of the mineralization, there is a data gap. If the drill density is only enough to define an Inferred Resource at the feasibility stage, the company is not going to be able to make economic forecasts/decisions on that resource.

When joining up sample points, whether drill holes or underground/surface exposures, it is important to consider very carefully the implications of what is being done. Data density controls the ability to resolve continuity — a large data gap will lead to poor continuity resolution. This has massive implications for effective grade and tonnage estimation (Dominy et al., 2003b).

Other continuity issues of concern include the effects of post-mineralization folding and faulting. It is important to know whether all faults have been intersected, their separation, whether there has been ore duplication or zones of 'fault want' (reverse versus normal faulting), and the estimated magnitude of displacement on each. There is always a possibility that some faults have remained undetected because of excessively wide drill spacing, or an unsuitable hole inclination. The impact of folding is also important, and whether it has resulted in duplication of horizons within the mineralized zone, incomplete intersections, and errors in true thickness estimates near fold axes.

Richards and Sides (1991) give an example from the Neves-Corvo copper-tin mine in Portugal, illustrating the development in conceptual geometry as additional geological information was obtained during exploration and development. When initial underground information was added to earlier exploration drill information, a greater structural complexity to the geometric continuity of the upper part of the Corvo orebody was observed. Subsequent close-spaced underground drilling and development showed that the picture was even more complex than the earlier simplistic interpretation. In another example, King et al. (1982) report that the initial interpretation of drill hole intersections some 135 m apart led to a 50% over-estimation of tonnage between the holes due to geometric variability in the Woodlawn lead-zinc orebody, Australia. These examples illustrate the uncertain nature of geological interpolation in relation to data density, even as production commences.

Orebody Limit and Domain Errors

The definition of the orebody limits relates to whether the assay contacts are sharp (hard) or gradational (soft) and whether the ore envelope can readily be defined between drill holes. If the orebody limits are highly irregular and the mineralization 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 evaluation process. These include post-ore dikes, fault zones and oxidized or leached zones. Prenn (1992) emphasizes the need for accurate boundary definition to constrain the block modelling process and prevent marginal smearing and grade dilution. In particular, he draws attention to the need to define structural discontinuities (faults) and boundaries between high- and low-grade mineralization and between different host rock lithologies.

Metallurgical Issues — Modelling Mineralogy

Failure to define metallurgical zones precisely may also 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. Geological modelling (domaining and wireframing) should thus accurately define the limits of such unique mineralogical zones. Sampling and testing for metallurgical purposes is critical through the development of a project.

Selection and Application of the Estimation Method

Introduction

The selection of the estimation method is one of the fundamental decisions made in the reserve estimation process. The effects of unsuitable estimation methods are well documented and alone could lead to errors of up to ±50% in the estimate. For a given orebody, the estimator needs to decide upon the domaining and 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. In particular, the data available should be used to the full, data extrapolation must be acceptable in terms of the true zone of influence of a sample, and the degree of grade smoothing/smearing beyond ore fringes should be known and appropriately flagged in the model. Recognition should also be given to the possibility of top-cutting or applying different ranges of influence of high-grade sample values so as to prevent unrealistic smearing of high grades or low grades in the grade estimate.

It is also important to assess the method by which the limits of ore are defined in relation to interpolation distance, irregularity and rate of thickness and grade diminution toward the fringes. Significant errors can occur at edges of data limits, including deposit, weathering and domain boundaries. Key areas of consideration during estimation include: effective use of data, data clustering, data density, suitability of the estimation technique, degree of extrapolation, model block size, number of samples used, degree of smoothing and smearing, effective construction of zone of influence/search area or volume, orebody domaining, definition of orebody limits, and semi-variogram modelling.

Estimation Method

The choice of estimation method is important, and must be carefully considered. The different techniques each have their relative merits and dismerits. The choice of method will be based on the geology and complexity of grade distribution within the deposit, and the degree to which high-grade outliers are present.

For example, polygonal methods may be suitable for producing a volume-weighted (declustered) global mean grade and tonnage of a deposit at no cut-off grade. However, if such a model is reported at a cut-off grade, then it is likely to report too selectively (i.e., fewer tonnes at a higher grade than reality) because the model mirrors the selectivity of the original sample grades and these are more variable and less diluted than the grades of large-volume mining blocks. In a polygonal estimate, there is just one biased and fixed answer from a given set of data (Dominy and Annels, 2001). It is not reasonable to expect to make an economic decision based on such an estimate.

Inverse distance weighting is unbiased but does not necessarily minimize the estimation variance. In linear geostatistics the estimate is subject to the satisfaction of certain conditions, namely, that it provides the best answer obtainable by a linear combination of the available weighted data by minimizing the error variance of the estimate. Alongside the estimate of grade for each model block, linear kriging also generates a value for the estimation variance. However, the geostatistical estimation variance is computed only from the sample point geometry and the variogram model, and does not take the actual data values into account. It is therefore not an absolute error that can be applied to the block estimate to provide confidence intervals. It is, however, an effective relative measure of the suitability of the sample density for estimating the grade of a specific block size in a deposit with a given grade continuity (as defined by the semi-variogram). Furthermore, for non-linear geostatistical methods (e.g., indicator kriging), the minimum-variance properties of linear kriging are lost and, as with non-geostatistical methods, it is not possible to produce estimates of the estimation variance.

Errors introduced during grade interpolation are also closely related to the model block dimensions relative to the spacing and density of the drill holes and the semi-variogram. The choice of appropriate block size is important as large blocks with dimensions approaching that of the sample spacing will improve the reliability of estimates. Smaller blocks will have increasingly high estimation variances. The small block problem has been documented by many, and refers to blocks that have small dimensions relative to the sampling grid and hence high errors in their estimate (David, 1977, 1988; Annels, 1991). The estimation and reporting of selectively extractable reserves at the expected scale of mining depends upon the confidence in local block estimates. Mine planning for selectively extracted deposits requires a grade-tonnage curve that reliably reflects that expected SMU behavior, however, this cannot be estimated directly from wide-spaced exploration data and this is why grade control drilling is essential during mining.

Whatever estimation method is selected, however, a major source of error is the problem related to heavily skewed data distributions and extreme grades (e.g., gold deposits). Careful attention should be paid to the impact of these outlier grades and different methods for estimating the weighted average of skewed populations from few sample data, including grade top-cutting, may be required. For example, significant errors can be induced into block grade estimates by inappropriate assignment of grade to the upper bins of Multiple Indicator Kriging gold populations (Vann et al., 2000).

Application of Conditional Simulation

There is a better method than the kriging variance 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 from kriging, conditional simulation is applied to simulate 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 realizations from the same sample 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 that does not take the actual grade values into account.

Conditional simulation results do not suffer from over-smoothing since the simulated grade values have the same variability and continuity (semi-variogram) as that of the conditioning sample data. The volume-variance correction is then accomplished by re-blocking the simulated grades into the required block shapes and sizes, essentially as would be carried out if exhaustive grade control sampling were available. The benefit of this is that the grade-tonnage curve for relatively small blocks generated from re-blocked conditional simulation data will be more reliable than that derived from direct block estimates using the available sample data (Assibey-Bonsu and Krige, 1999). Allowance should also be made for mining loss and dilution when reporting a practical grade-tonnage curve for a project. 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 at a given level of sampling information. These results generally better represent the expected Ore Reserve behavior at a range of cut-off grades than the single grade-tonnage curve produced by traditional resource estimation methods.

Summary

Whichever estimation method is used, it must be chosen and applied within a strict framework of geological understanding and high-quality data of an appropriate density and distribution. Advanced geostatistical methods cannot make up for missing or poor quality data. Geology should guide resource estimation, not resource estimation guide the geology (Dominy et al., 1997, 1999; Sinclair, 1998; Dominy and Annels, 2001; Duke and Hanna, 2001; Dominy and Hunt, 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 better chance of being of appropriate reliability. As part of the on-going QA/QC program, the essential step of resource validation must be undertaken.

Mine Planning Uncertainty

Assessment of Mining Constraints

An Ore Reserve estimate is based on the Mineral Resource modified with appropriate economic, 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 mineralized zones, the regularity of wall contacts and the strength of the ore and wallrocks (e.g., geotechnical issues). Both open pit and underground Ore Reserves are strongly dependent upon various considerations, including the following:

- spacing of sample data relative to SMU size;
- confidence in sample positions;
- bench heights;
- planned grade control;
- size of model blocks in relation to SMUs;
- minimum stoping widths;
- choice of stoping method;
- dilution factors (planned vs unplanned);
- geotechnical and hydrological parameters;
- mining recovery factors;
- metallurgical recovery;
- requirements for exclusion of internal waste;
- 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.

The confidence in grade estimates in a given model block size is dependent on survey accuracy, sample density and grade continuity characteristics (geostatistical ranges and degree of anisotropism). The size of anticipated selective mining units (SMUs) might be considerably smaller than the model blocks used to estimate the Ore Reserves. Thus corrections must be made to allow for this during feasibility studies to derive an appropriate grade-tonnage relationship, recognizing that the variability of grade among SMUs will be considerably greater than that for the reliably estimated larger model 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. For this reason, estimators should be encouraged to report the model block size on which the Ore Reserve is based.

Many Ore Reserve estimates do not carry explicit warnings that they relate only to a particular choice of mining method. However, the selection of mining method (e.g., 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 smaller tonnage and higher grade, others larger tonnage and lower grade.

Open pit and different underground reserves may even be geometrically quite different due to the differences in physical constraints of each mining method, and the underlying block models may require different methods of preparation. The selection of the best mining option may often be far from obvious, including the decision on where to change over from open pit to underground. 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 errors of ±40% or more. Butcher (2000) reports figures for dilution in some African underground mines ranging from 18% to 115% for sub-level open stopes, 27% to 48% for up-dip retreat stopes, and 5% to 15% for cut-and-fill stopes. Mining dilution (also recovery) is difficult to measure and more difficult to predict. There is no alternative to careful measurement (e.g., use of CMS systems; Miller et al., 1992) coupled with experience-based adjustment (McCarthy, 2001). For reserve purposes, dilution must be estimated from data obtained from diamond drilling and development, and from experience. Key variables include the mining method and equipment size, grade variability at the resource boundary, ore geometry and continuity, proposed mining rate and stope design criteria (e.g., hydraulic radius, RQD and pillar dimensions) and the physical characteristics of the waste material and the ore/waste boundary.

The classification of Mineral Resources and Ore Reserves may also depend on the anticipated mining method. For example, a resource prepared for bulk open pit extraction may attain a Measured Resource status, but the same resource model would be inappropriate for detailed underground mining design.

Economic and Other Uncertainties

Economic inputs into the Ore Reserve estimate are also critical. The list below is self explanatory and it suffices to say that each parameter has a potential error in its estimation, 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.

- Mining and processing costs (operating and capital).
- Break-even cut-off grade.
- Minimum mining grade (operational cut-off grade).
- NSR factors for individual metals.
- Break-even NSR.
- Depreciation factors for NPV analysis.

The JORC definition of an Ore Reserve includes the following words: "*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 that 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. There is a widespread tendency to be satisfied too early with geological data and information, the geological model, resource/reserve estimates, and to tolerate incomplete tests, design, planning, etc., and only face the solution of these problems once mine project financing is available. All the geological and technical sources of uncertainty should have been solved or quantified at the time of the feasibility study on the basis of the quality assurance programs and of the audits carried out at successive project stages. Conditional simulation methods can play a role in improving the confidence in relation to the grade/tonnage aspects of geological reporting, but only in as much as the sampling, quality, density and distribution are adequate.

Monitoring the Reserve — Reconciliation Studies

Systematic reconciliation studies provide the ultimate model validation and reality check and provide a means of monitoring the quality of the Ore Reserve estimate produced from exploration data for the feasibility study and the grade control estimate. Studies can be designed to investigate input data (e.g., sampling quality, database entry, etc.), reserve modelling (e.g., geological interpretation, grade interpolation methodologies, volume estimation, etc.) and checking of the final Ore Reserve model (e.g., comparison of different models, etc.). Reconciliations involve comparisons between the tonnages and grades of any of the following (Gilfilan and Levy, 2001):

- Mineral Resource estimates;
- Ore Reserve estimates;
- short-term grade control estimates (for in situ resources or “mineable” reserves);
- 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. Favorable reconciled estimates will lead to increased confidence of forecasts of future production.

Part 3 — Reporting Errors and Uncertainty

Introduction

Transparency in the reporting of resource and reserve estimation errors and uncertainty is becoming more important in the international mining industry. Methods of stating risk/uncertainty range from simple “risk matrices” through to complex geostatistical simulations. All estimates at the very least should include a risk matrix to inform the reader of the key issues present in that estimate. If possible, actual confidence levels can be determined through geostatistical applications, providing the data quality is there to support them. A discussion of potential risk/uncertainty reporting methods follows.

Better General Disclosure of Project Issues

More open and effective disclosure of project issues is a key way for companies to be more transparent. Quite simply, resource reports need to contain more discussion of key issues, particularly those that will potentially impinge negatively on project economics and viability. Disclosure should be clear, concise and unambiguous.

For example, the use of the grade estimates quoted within ‘grade ranges’ is recommended for high-nugget effect gold deposits to achieve more complete disclosure on grade variability (Dominy et al., 2001; Dominy, 2002b, 2004b). The key issues are clearly the definition of the grade estimate and the “grade range.” The grade can be estimated by various techniques ranging from simple weighted averages to geostatistical block modelling methods. The definition of the grade range is often somewhat subjective, but depending upon the data available could involve study of bulk sample grades through to conditional simulation (Dominy, 2004b).

The Risk Matrix

Every report of Mineral Resources and Ore Reserves should include a statement of all the relevant risks inherent in that estimate. It should include a clear statement of all significant sources of error and, where possible, the likely magnitude of error due to each, and the likely impact or significance of each.

For example, Table 5 shows a simple risk matrix for a gold vein pre-feasibility study that conveys simply and effectively the nature of risk in that estimate. The matrix is based on a global resource estimate to Inferred Resource level. A six score classification can be employed where: (1) “low” risk means little or no perceived risk is attached to

Table 5. A simple matrix can be used to convey the resource risk for a project

Factor	Risk Score
Diamond drill core logging	1
Bulk density data	1
Gold assay data	1
Hole survey data	1
Grade estimate	4-5
Tonnage estimate	5-6
Geological interpretation	5-6

Note: The data presented here is from a low-nugget effect low-sulfidation epithermal gold vein deposit at the pre-feasibility stage.

that aspect of the estimate (low uncertainty); (3) “moderate” means that there is a risk that this aspect of the estimation process/data could lead to non-material error in the final resource model; and (6) “high” means that this aspect of the estimation process could lead to material error in the final resource model (high uncertainty).

In this case, the highest risk factor for resource estimation is geological interpretation, and is reflected in the score for the grade and tonnage estimate. The current drilling density (40 m by 15 m to 40 m grid) is insufficient to reasonably define the orebody geometry. In particular, small-scale faulting could significantly impact on the inventory of potentially mineable material. Data quality (e.g., assays, down-hole surveys, etc.) is considered to be high with a consequential low risk and uncertainty. A full QA/QC program was undertaken during the pre-feasibility drilling program including external and internal audit; sampling, sample preparation and assaying protocol optimization and control; and data validation, etc.

More complex risk tables can be devised if required for more advanced and detailed studies. This may lead to documents that appear less friendly to the project developers and financial experts but which should be more meaningful to the investors, reviewers or auditors of the project. This would also ensure that in the operational environment the entire mining team are aware of the likely problems.

Such clear and transparent reporting is one of the main aims of reporting codes such as the JORC Code (JORC, 1999) and others. It should not be acceptable to report reserves as precise tonnages and grades without any indication of the uncertainties involved. The categories of Measured, Indicated and Inferred for Mineral Resources, and Proved and Probable for Ore Reserves provide a relative level of confidence in the estimates. However, the reporting codes do not attempt to quantify the associated levels of confidence for these categories, and that is the challenge for the CP preparing such reports.

Conditional Simulation

Principal Application

There is no one statistically rigorous way of estimating and reporting the degree of uncertainty in any set of resource and reserve figures. Block grade kriging variance estimation errors are not useful quantitatively (Henley and Watson, 1998; Dominy and Annels, 2001). However, the technique that is increasingly applied for modelling uncertainty in grade (and tonnage) estimation is conditional simulation (Thomas et al., 1998; Coombes et al., 2000; Khosrowshahi and Shaw, 2001, Snowden, 2001; Jackson et al., 2003). The resultant range of equally likely grade and tonnage outcomes from conditional simulation can be used to quantify and report the risk in the model estimates at any cut-off grade, or for changes in block size, stope size and/or for different mine layouts for different mining periods. The grade and tonnage (or metal and hence value) can be expressed as a range of uncertainty at a quoted confidence level, and the original resource estimate can also be benchmarked or calibrated against the simulated results. Clearly, the narrower the range of outcomes and the higher the confidence level, the less the risk. With time, experience may allow this to form an important element for determining the classification status of resource estimates as Measured or Indicated. For example, an estimate of the grade to within ±5% at a 90% or better confidence level for a quarterly period may class the resource as Measured, while estimating the grade to ±5% at 75% to 90% confidence for a quarterly period may class the resource as Indicated (assuming all other relevant criteria are reliably known).

Conditional simulation has also been applied for determining the sensitivity of the model to uncertainty in deposit boundary positions where such boundaries are not obvious (so-called morphological or categorical kriging). In other examples, the distribution of the mineralized portions of the deposit, for example the quartz veins, have been simulated, followed by the simulation of the grades, thus performing both a tonnage and grade risk assessment (Dowd, 1996). 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 and is subsequently seldom referred to after the initial geological modelling has been completed.

Conditional simulation on resource variables requires the same rigour in domain interpretation, geology, modelling of grade continuity and the selection of simulation method as is applied in kriging. Uncertainty in the input data values may be incorporated in the geostatistical nugget effect, but the origin and applicability of this randomness to later grade control conditions should be understood. Grade control sampling for ore control may have a higher or lower nugget, which may impact in the ability to select the ore and waste boundaries. Conditional simulation for the reserve should ideally include an assessment of the additional sources of uncertainty: dilution, loss and extraction expectations, and the conditional simulation results for reserve reporting may need to include an allowance for such factors (Snowden et al., 2002).

Additional Applications of Simulation

Standard approaches to risk analysis often involve Monte Carlo simulation. A model is constructed which gives as complete as possible a representation of all of the sources of uncertainty and error in a given industrial or economic process. Each step in the model is simulated a large number of times using random or pseudo-random numbers to represent the degree of variability — and if possible model the actual distribution of errors — in the inputs to that step.

There is no basic difficulty in carrying out such a simulation for most steps of the reserve estimation model. However, the selection and optimization of mine designs for varying models can be challenging. Given a single basic model it may be possible to apply fully automated optimization methods to allow the entire simulation to be carried out automatically. If this cannot be done, then there would be a non-trivial manual step (the mine design) which would have to be repeated many times on the different simulated data sets; in such a case, it could well become impractical to carry the Monte Carlo simulation through to the final reserve model. One solution would be to consider only the best, worst and median options derived from the simulation results to represent the range of likely outcomes for consideration in the mine planning scenarios. Similarly, if early-stage data show so much variability that there could be widely differing geological interpretations, depending on the input sample data, it might be pointless in practice even to do a Monte Carlo simulation of the resource. However, it should be possible in most cases to decide qualitatively on the geological interpretation and on the type of mine sufficiently to allow a fully automated Monte Carlo simulation to be set up and performed.

By incorporating all of the possible sources of error into a detailed Monte Carlo simulation (with grade estimation by conditional simulation), the resulting set of resource and reserve models will yield error estimates which incorporate all of the identified sources of error. In reality, the combination of all the possible uncertainties may provide a very real 'wake-up' call to the project team. Perhaps this is the reason why such all-encompassing risk assessment techniques have not been widely publicized.

Resource Reliability Rating System (RRR)

A review of the sources of error naturally leads to the assignment of scores to each stage of the evaluation process. Such an approach was first proposed by Annels (1995a, 1995b, 1996), and further developed in Annels (1997) and Annels and Dominy (2002). For example, core recovery is an important factor that has a number of potential implications for estimate quality (Table 6; Annels and Dominy, 2003).

A series of questions can be posed, and then scored depending upon the answer. Part of the scoring for core recovery could include questions and scores as follows:

1. What type of sample was collected?

❑ Core
❑ Chippings

If core, then:

2. How would you describe the quality of your cores?

	Score
a) Continuous undamaged core	5
b) Long lengths of core with some short broken intervals	3
c) Broken and continuous core - 50:50	1
d) Only minor amounts of unbroken core	-3
e) Broken and/or unconsolidated core	-5

3. Were core recoveries of less than 95% found in the following percentages of holes?

<20	20-40	40-60	60-80	>80
-1	-2	-3	-4	-5

4. Were the following parameters measured in core?

Total core recovery	Solid core recovery	RQD	None
2	1	1	0

5. Indicate the average core recovery (total core recovery) for the project.

<60%	60-70%	70-80%	Not measured	80-90%	90-95%	>95%
-5	-3	-1	0	1	3	5

Other questions/scores related to core recovery could include: what action was taken for intersections with excessive core loss; what method was used to determine the grade of samples with high core loss; was core recovery block modelled along with grade, thickness and metal accumulation, etc.

These and the other scores (Table 7) can then be weighted and combined in a manner resembling that used in the CSIR Rock Mass Classification (Bieniawski, 1989) to produce a Quality Control Index (QCI). However, this index must be modified using an Evaluation Difficulty Index (EDI), which reflects the hostility of a particular style of mineralization to accurate resource estimation. A similar weighted score system would be applied as for the QCI following responses to a series of questions which relate to the geological and grade characteristics of the deposit under scrutiny. Such a modification is necessary as it is possible for a project to have a high QCI due to the quality of the sampling and evaluation exercise but to have a very poor EDI due to the intractability of the deposit. The combined result is a Resource Reliability Rating (RRR), which more accurately reflects the combined economic risk in a resource/reserve estimate. The RRR allows the estimate to be rated on a scale from 0 to 100% and its incorporation into international classifications, such as the

Table 6. Impact of core loss

Problems	**Error**
Depth and thickness estimation	Global tonnage
Grade estimation	Global tonnage and grade and local tonnage factors
Tonnage factor estimation or measurement	Global and local tonnages
Geological interpretation	Incorrect geological and block model
Geotechnical analysis	Mining recovery and dilution

Table 7. Key topic areas for scoring using the RRR system

General Topic	**Specific Sub-topics for Scoring**
Geological assessment	QA/QC program, data density, data location, geology/ mapping, core logging system, geological model, geology database construction and validation, etc.
Tonnage estimation	QA/QC program, boundary definition, bulk density, etc.
Grade estimation	QA/QC program, data density, data location, sample collection (incl. core recovery), sample preparation, assaying, database construction and validation, orebody domaining, grade interpolation method, etc.
Final resource estimate	QA/QC program, validation and checking, reporting, etc.

Note: Each sub-topic will require a series of questions for scoring like the example given in the text for core recovery. The list of sub-topics is not exhaustive.

Table 8. RRR classification and potential linkage to the 1999 JORC Code

Score	Confidence	JORC Class
100-90	Very High	Measured Resource
80-89	Good	Indicated Resource
60-79	Moderate	Inferred Resource
40-59	Poor	
<40	Unacceptable	

1999 JORC code, to more precisely define geological confidence levels (Table 8). This rating can also be used as the basis for technical audits of mineral projects and permit the self assessment of an estimate during production.

Concluding Comments

Resource/reserve estimation is not simply a measure of maximum NPV or return on investment, but involves other corporate objectives, both quantitative and qualitative. Uncertainty and even blatant errors in estimates remain a major source of economic failure in the mining industry (Hall, 2003). The suitable application of computer-based estimation and analysis can enable a more precise Ore Reserve to be defined within a given mineralized resource, or at least the expected range of estimates to be reported. Methods such as conditional simulation are also available to quantify and report 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.

A major source of error in resource and reserve estimates can be attributed to the grade and its physical limits. There should be no compromise for good data of appropriate density and distribution. Besides the importance of suitable sample collection, preparation assaying and database preparation, the error in resource/reserve grade interpolation estimates is arguably the most difficult to improve. In some cases, costly large-scale increases in data density may be the only way forward. A major stumbling block to reliable grade estimation and reporting has historically been the lack of understanding and honoring of the volume-variance effect in grade interpolation. Better methods to report and convey the confidence in the estimates are essential.

It must be recognized 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. Above all, resource and reserve error can be markedly reduced and controlled by the careful implementation of quality management and continuous improvement programs throughout the entire life of a mining project.

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