Core recovery and quality: Important factors in mineral resource estimation

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Technical note

Core recovery and quality: important factors in mineral resource estimation

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Introduction

The estimation of mineral resources is critical to all mining operations irrespective of size or commodity.[1,12] The risks associated with mining are varied and complex, where the dominant source of risk is the orebody itself. Reverse circulation (RC) and diamond core drilling methods are used extensively for the collection of samples from depth. These data generally form the critical base for both geological and grade modelling, leading to the mineral resource estimate and ultimately the ore reserve estimate. It is well known that diamond drilling generally provides a higher quality sample, better suited to resource estimation than RC drilling, especially for gold deposits.[1,6,7,11] RC methods are sometimes applicable to the resource evaluation of alluvial/unconsolidated deposits, though can be highly problematic when applied to gold deposits.[7] Current methods of resource classification relate to the geological, economic and technical confidence in the resource.[14–16] Geological confidence is largely related to the level of drilling and sampling in the orebody, to the geologist's perceived level of confidence in his or her work, and to the continuity of the mineralisation. This contribution reviews the geological and technical factors that affect core recovery, how core recovery is measured, the impact of poor recovery on the resource estimate, and how to deal with lost core during estimation.

Potential sources of error

Many potential sources of error exist which will affect the accuracy of resource estimates at all stages.[1–3,12] These will combine to enhance the random component of the data variation, and thus contribute to nugget variance. Errors can be introduced at a number of stages including, drilling and core logging, geological mapping, sampling, assaying, geological modelling and grade/tonnage estimation.

The effects of poor sampling regime at any stage of a mining operation can introduce unpredictable random errors, and negative or positive bias into the estimate. Some of the sources of error that may be related to drilling include: (i) inappropriate drill hole inclination relative to orebody dip; (ii) poor core recovery and quality; (iii) blocking errors; (iv) selection criteria for sample length; (v) poor quality sampling practice and/or sampling bias; (vi) poor sample preparation protocols; and (viii) core handling and checking (including tampering with, and removal of, core).

Core recovery and quality

The precision of estimation is very much dependent on the quality of the sample database. The application of sophisticated computer techniques will not offset poor data quality and often renders the results meaningless. It is thus essential that the **quality** and **quantity** of samples recovered be maintained at a high level.

Core loss is a relatively common occurrence during diamond drilling, though there is very little information in the literature on how to deal with it. Intersections to be used in a resource estimate should have a total core recovery (TCR) value of at least 85%, and preferably greater than 90%.[3,10] The attitude that recovery measurement is unimportant or even unnecessary must be dispelled. If recovery cannot be maintained at high levels due to technical or geological problems, then it is important that this fact is not concealed. Allowances should be made for loss of sample in the resource estimate and/or in its subsequent classification. This requires that the geologist make the effort to measure core recovery carefully and incorporate this information into the computer database. It is unacceptable to estimate recovery or to assume that it is 100% – a rare occurrence, but sometimes observed. Where excessive core recovery (> 100%) is recognised, it is important that attempts be made to determine the reason. This may be purely due to displacement of marker blocks during handling and transport, or to stick-ups at the bottom of the hole after one drill run which are picked up during the next run. In this latter case, the preceding run will show an apparent core loss. This problem should be rectified before sampling of the core.

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Technical factors affecting core recovery

The following list presents a summary of some of the factors that could contribute to either low recovery or to badly broken core, even in good ground conditions:

(i) bent inner tube so that: (a) the core will not travel up the tube and will be subject to grinding; (b) it rotates with the outer tube again disturbing and grinding the core; and (c) it fails to seat properly in the outer barrel resulting in total core loss
(ii) failure of back-end bearing resulting in: (a) loss of core due to grinding; and (b) grinding of core leaving flat faces
(iii) bent outer tube of core barrel resulting in: (a) failure of the inner tube to latch in and thus loss of core; and (b) less than full diameter cores
(iv) core spring missing, displaced, damaged, worn or not lubricated
(v) badly worn or damaged crowns
(vi) diamonds inside kerf damaged, worn or displaced causing core to jam in inner tube
(vii) worn stabilisers
(viii) vibration induced by poor equipment, insecure rig mountings and hole deviation
(ix) blocked waterways
(x) inadequate flow/pressure of flushing medium and unsuitable flushing medium
(xi) loss of water return
(xii) excessive/inappropriate head pressure and rotation rate
(xiii) inexperienced driller or driller chasing production bonus.

A major cause of poor core quality and loss, is the failure of the wireline inner tube to seat or latch properly. This usually results from bent inner/outer tubes, wrong inner tube length, latch failure (broken spring), or a hole angle that is too shallow to allow the inner tube to travel.

Geological factors affecting core recovery

A summary of some of the geological reasons why core recovery may be poor is presented below:

(i) soft friable ground due to alteration, weathering or leaching
(ii) unconsolidated materials
(iii) broken ground with clay infill
(iv) soluble components removed by unsuitable flushing medium
(v) low intersection angles with rock discontinuities (cleavage, open bedding, joints, schistosity, foliation, *etc.*), particularly joints following the core axis, and cleavage disking leading to a 'rasher of bacon' effect in the inner tube
(vi) high frequency of discontinuities per metre
(vii) unexpected fault zones
(viii) secondary porosity or vug development due to karstic solution or dolomitisation or hydration of anhydrite
(ix) cavities induced by karstic weathering along joints and faults and also mining (stopes and caved zones)
(x) alternating rocks of variable hardness and abrasiveness
(xi) over stressing (disking on stress release)
(xii) sheared or brecciated host rocks associated with mineralised zones
(xiii) high clay content leading to blocking of waterways/airways
(xiv) water saturated ground.

Many of the above problems can be ameliorated by the use of larger diameter barrels, a more suitable flushing medium or the use of triple-tube barrels. In the case of broken ground, which quickly results in the blocking of the inner tube, the use of shorter drill runs is recommended, thus not attempting to fill the inner tube to capacity.

Measurement of core recovery

The measurement of recovery is a key part of the core logging process, which includes recording geological information and taking samples.[13,17] The overall logging exercise is one of great importance and should not be left in the inexperienced geologist/geological technician.[13]

During core sampling, errors can be induced by the selection of unsuitable sample intervals in relation to changes in mineralogy, host lithology, metallurgy, *etc*. 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 no satisfactory way has been proposed to allow for the fact that we know nothing about the grade of the portion of the core that has been lost.

Heavy core losses throughout an ore body intersection can seriously undermine the confidence in a resource 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. It is important to determine whether a relationship exists between grade and recovery (either positive or negative) to assess the potential for grade bias.

Assuming that depth measurement and blocking has been done correctly and checked prior to logging, core recoveries can be determined using the total core recovery (TCR) parameter, which is defined as:

$$\text{TCR} = \frac{\text{Total length of core recovered}}{\text{Drilled length}} \times 100 \qquad \text{Eq. 1}$$

However, this hides the fact that the quality of the core may be poor and the measurement of solid core recovery (SCR) is more relevant:

$$\text{SCR} = \frac{\text{Total length of core in pieces} > \text{core diameter}}{\text{Drilled length}} \times 100 \qquad \text{Eq. 2}$$

For example, with NQ diameter core (47·6 mm), only core pieces greater than 47·6 mm are counted in the determination of SCR. Core sections of this length are only included if a full core diameter exists. If a core piece has a length of 60 mm, but does not possess a full core diameter (i.e. is split longitudinally), it is not counted.

Barton *et al.*[5] suggests that TCR, and by default SCR, should be measured and reported to the nearest 2%.

Where geotechnical logging accompanies the geological logging (and it should), the rock quality designation (RQD) may be determined.[5,9] RQD is a modified core recovery percentage and can be taken as a measure of core quality. The RQD was developed to provide a quantitative estimate of rock mass quality. It is the percentage of intact core pieces longer than 100 mm in the total length of the core:

$$RQD = \frac{\text{Length of core in pieces} > 100\text{ mm}}{\text{Drilled length}} \times 100 \quad \text{Eq. 3}$$

The core should be at least NQ (47·6 mm) and drilled with a double- or triple-tube core barrel. Care must be taken to ensure that fractures, which have been produced by handling or drilling, are identified and ignored when determining the RQD value. Material that is obviously weaker than the surrounding rock (such as over-consolidated gouge) is discounted, even if it appears as intact pieces that are 100 mm or more in length.[5] The length of individual core pieces should be assessed along the centre line of the core, so that discontinuities that happen to parallel the drill hole will not unduly penalise the RQD values of an otherwise massive rock mass.[5] It is recommended (for geo-mechanical purposes) that RQD be determined for variable rather than fixed lengths of core run. Values of individual beds, structural domains, fracture zones, *etc.* should be logged separately, so as to give a more accurate picture of the distribution and width of zones with low RQD values.[5]

RQD and, indeed, TCR and SCR are directionally dependent parameters and their values may change significantly, depending upon borehole orientation. This feature must be carefully considered in the interpretation of such data.

Table 1 shows a comparison between TCR, SCR and RQD for three intersections within the same quartz vein. An NQ core barrel was used. Core A has a TCR value of 83% that, whilst not good, is fair. However, the corresponding SCR and RQD are 51% and 30%, respectively, and reveal the true poor quality nature of the core.

Table 1 Comparison between core properties of three 3 m intersections within the same orebody

Feature/property	Core A	Core B	Core C
TCR	83%	99%	96%
Variation from 3 m of core	–51 cm	–3 cm	–10 cm
SCR	51%	57%	96%
Number of >48 mm core lengths	13	12	11
RQD	30%	0%	96%
Number of > 100 mm core lengths	5	0	11
*Rock quality	Poor	Very poor	Very good

*Based on relationship between the numerical value of RQD and the engineering quality of the rock proposed by Deere.[9]

Core B shows a TCR of 99% indicating an excellent recovery; however, the SCR and RQD values of 57% and 0%, respectively, reveal the true very poor quality of the core due to severe fragmentation. In such a situation, the measurement of TCR is very difficult, as it can only be determined after an attempt to reconstitute it to its prefragmentation equivalent. An intersection could return a TCR > 100%, which could be due to measurement problems or displacement of depth blocks. However, excessive recovery could also be due to retrieval of core left behind in the hole after the previous drill-run. Core C is the highest quality and receives a 96% score for each measure. There is very little fragmentation of the core; it is composed of 11 > 100 mm lengths.

The key conclusion from this information is that TCR alone is not the best indicator of core quality (Table 1 & Figs. 1–3). It is strongly recommended that all three parameters are determined during logging. The extra work involved in doing this is relatively minimal in the big picture, and worth the extra information. The measurement of RQD will aid mine-planning engineers at a later date.

Impact of sample loss (poor recovery) on the resource estimate

If core is lost in a mineralised interval or badly broken and disturbed, it presents three major problems: (i) depth and thickness estimation is difficult for specific lithological or grade zones in the overall mineralised zone; (ii) accurate estimation of the grade is impossible; and (iii) accurate determination of tonnage factor is impossible.

In the first case, this affects the thickness used to weight the associated grade having a knock-on affect on both tonnage and local or global grade; in the second case, this not only affects the final grade estimate but also affects the delimitation of ore fringes (vertical and lateral) based on a cut-off grade which in turn will affect the tonnage estimate. If the material lost is of lower grade than the recovered section then overestimation of grade results and a sample, which should, perhaps, have been allocated to waste, is incorporated into the potential ore zone. Conversely, if the lost material is of higher grade, the resulting underestimation results in the loss of ore zone thickness if the sample is at the margin or underestimation of the grade of the ore zone. Badly broken core may present problems in recognition of grade changes during sampling and also biased sampling due to the difficulty of making an accurate longitudinal split of the core. This further exacerbates the grade estimation problem.

In the case of the third problem referred to above, tonnage factors can be calculated from assay grades; however, if these are suspect due to uncertainties as to the grade of the lost core, then the bulk density will be in error. Alternatively, if bulk density is directly measured on core then the assumption is made that there is no change in its value between the recovered and lost sections. The loss may reflect poor ground which, in turn, may be reflected in lower densities.

1 Mineralised core length of 4·20 m from an epithermal gold system in Australia, with at least 25% of the zone poorly recovered. The TCR value for this run is 73% (moderate recovery), whereas the SCR and RQD values are 55% and 49%, respectively (poor quality)

Also, if the core is fully recovered but is in bad condition, then it may be impossible to obtain a representative measurement.

Dealing with lost core

Since core loss is a relatively common occurrence, the question is how to assess losses so that undesirable bias, to either lower or higher values, are avoided during estimation. The practicalities of dealing with mineralised intersections that show poor recovery (e.g. < 85% TCR and SCR) are not simple. Geological observation and experience are very important if core loss does occur. For example, does the mineralisation mainly occur on fractures, or is the core recovery lower in strongly fractured or broken zones? Is the mineralised zone softer than the surrounding rocks? Such observations can help in controlling potential bias.

If there are differences in the core recovery within a deposit, then the homogeneous zones should be selected according to the same degree of core recovery. These zones can then be subdivided according to their geology. It is very important not to combine a zone of say 100% recovery with a zone of 45% recovery into

2 Mineralised core length of 4·35 m from an epithermal gold system in Australia, showing excellent recovery (TCR = 95%), but poor quality (e.g. fragmented). The SCR and RQD values of 58% and 41%, respectively, support this observation. Without the SCR and RQD values, the resource estimator would have no idea of the quality of this intersection. It is highly likely that; (i) fine material is missing from the intersection; and (ii) that the sampling/core cutting process was poor due to the broken core. Any intersection grade(s) produced from this core is likely to be suspect

3 Mineralised core length of 4·60 m from an epithermal gold system in Australia, showing the ultimate aim of any resource drilling programme – 100% recovery (TCR) and good core quality (SCR 99% and RQD 99%). With good sampling and assaying protocols this intersection should produce high quality grades for the resource database

one sample. These zones of differing recovery should be separated otherwise errors are compounded through different sample supports.

The project stage and database size also has some bearing on the magnitude of the problem. Clearly, if only three or four intersections out of, for example, a few hundred are below 85%, then the issue is potentially not significant. However, if many intersections show a poor recovery (say 50% with < 85% recovery) at the prefeasibility/feasibility stage, this raises the questions of: (i) is the database valid for resource estimation; and (ii) should more drilling be undertaken to see if better recoveries can be achieved? In some instances of very poor ground conditions, then RC drilling may have to be used. In whatever situation, how should these poor quality samples be treated and what grade should be put into the database?

Core loss and sample support

Sample support is an important geostatistical consideration that refers to the volume and size of a sample. Taking NQ core as an example, a 1 m length of core has a different support to that of 0·25 m length of core. Similarly, 1 m of NQ core differs from 1 m of BQ core. In the core loss framework, we have a support issue when; for example, 0·5 m of recovered core is being used to represent a 1 m composite. David[8] noted an example for a low nugget effect, highly continuous orebody, where the support discrepancy is not problematic as the variance between the two supports (6 inches and 10 feet, respectively) is not great. However, in less continuous ore with a higher nugget effect the situation is very different, where the small sample (poor recovery) variance is much higher than the larger sample variance. In such as case, there would be a very real danger of not properly resolving the semi-variogram model, especially any small-scale structures, with the mixed sample population. Of course this situation will only be a problem if a substantial number of samples have a poor recovery.

Investigation recovery-grade bias

Where poor core recovery is notable (say at least 20–30 intersections) it is worth producing X–Y plots of core recovery (SCR and TCR) versus grade (%, g/t, *etc.*). This will allow the relationship between recovery and grade to be investigated. A simple regression calculation will permit the nature of any grade bias to be determined. If the regression line is zero, then there is no correlation between recovery and grade. If a random scatter is produced, then there is a negative correlation and core loss can be suspected of causing a positive bias – thus grades of mineralisation appear higher than they are. If the gradient of a best-fit regression line is positive, then a negative bias is likely to be present. This is a useful method for investigation of recovery bias, but it should be used intelligently. For example, it is possible that grade can correlate with the mechanical properties of the rock, in that the softer sections with poor core recovery will in reality have a high grade.

Methods to deal with core loss and grade

There are a number of methods that have been used calculate the grade of an intersection with poor core recovery. These are summarised briefly below.

One approach is to consider only the recovered core. Thus, if the recovery of a 1 m section has a 50% (TCR) with a grade of 2 g/t Au, then it is assumed that the mineralised intersection is 0·50 m thick at 2 g/t Au. As a consequence, the tonnage in this region is reduced and it is assumed that the assayed grade is correct for that intersection. The latter of course may not be true.

Table 2 Confidence rating of core recovery values (SCR)

Core recovery (SCR)	Rating	Description
> 85%	4	High confidence
60–84%	3	Moderately reliable
30–59%	2	Unreliable
< 30	1	Unacceptably low

Another and very common approach is to assume that all lost material has a zero grade, but take thickness to be that represented by the core. Whilst this is unlikely to be true, at least the estimate will be conservative in its underestimation of grade. Thus with our 1 m section at 50% (TCR) and 2 g/t Au grade, we take this as 1 m at 1 g/t Au calculated from:

$$G = \frac{\Sigma^{n}_{i=1} \text{(Recovered core grade} \times \text{Recovered core length)}}{\Sigma^{n}_{i=1} \text{(Represented length)}} \qquad \text{Eq. 4}$$

The criticism of this method is that it assumes that the non-recovered core has zero grade, which is unlikely, but at least there is less chance of over-estimation of grade.

Other approaches have included setting the lost material grade to the deposit average, the average of the two closest samples (e.g. mineralised samples either side of lost core) or some sort of weighted grade.

Baker and Binns[4] used a weighting approach, where gold grades were reduced, on the basis of core recovery to a nominal 95% TCR. For example, a 1 m interval, with 50% recovery and an assay value of 2 g/t Au, would be calculated as 1.05 g/t Au according to:

$$G = \frac{(2 \text{ g/t} \times 0.5 \text{ m})}{(1 \text{ m} \times 0.95)} \qquad \text{Eq. 5}$$

A further approach to dealing with core loss is to undertake a point kriging exercise down the hole. The aim here would be to estimate a grade for the missing core based on interpolation from high-quality mineralised samples (e.g. > 85% TCR and SCR) up and down the hole from the poor recovery interval. The definition of down-hole variogram parameters would be a critical part of this exercise, following de-regularisation of the original composite samples. Clearly, this method is only applicable to thicker deposits where a large number of samples are present. It would not be applicable to a 1 m narrow vein system for example.

An alternative approach to dealing with core loss

Rather than attempting to correct for the impact of core loss on grade estimation, an alternative approach might be to accept the grade information for all the samples, but to assign individual confidence ratings to each. This is based on ranges of TCR or SCR. For example, we could rate the sample for resource estimation as shown in Table 2.

Where the SCR is low, or there are other reasons to assign a low confidence to a sample, then this rating could be further reduced by say 0·5. This methodology has been used to down-rate sample data obtained from old drilling campaigns, where the sampling procedure was non-standard and where there were doubts as to the quality of the analysis. In this particular instance also, check re-sampling was only possible in a small percentage of the holes originally drilled. Confidence was then further reduced justifying the deduction applied.

Table 3 Confidence rating of RC recovery values

Statistical basis	Rating	Description of confidence
Mean ± 1 SD	4	High
Data beyond above to +2 SDs	4	High
Data between 1 and 3 SDs below mean	3	Moderate
Data above mean +2 SDs	2	Unreliable (contamination)
Data below mean –3 SDs	1	Unacceptable loss
No recovery or cavity	0	No grade assigned

A similar approach can be made in the case of RC samples where the rating is based on a statistical analysis of the sample weights recovered over constant hole lengths. This approach was applied in a situation where the theoretical weight of each sample could not be precisely determined due to variability in the nature of the mineralisation, its competence and in the quantity of vugs and solution cavities intersected. The population was clearly bimodal, with the dominant one reflecting the natural variability of the mineralisation and the second, lower, population the product of heavy sample loss. All sample weights less than the mean minus three standard deviations ($\bar{X}-3\sigma$) of the dominant population were assigned a low rating (Table 3). Similarly, any sample whose weight exceeded mean plus two standard deviations ($\bar{X}+2\sigma$) was also given a low score. This value closely corresponded with the maximum possible weight of a sample. The rating system applied is shown in Table 3.

Where the field geologist's log indicated a problem due to possible contamination, sampling bias due to water injection or the intersection of groundwater, these ratings were down graded by 0·5. This system allowed both RC and diamond drill data (both old and new) to be combined into a single confidence database. This information was then kriged into each resource block along with grade, and used as a basis for resource classification. Measured and indicated mineral resource categories were defined in areas of uniform drilling density and, where there was a combination of low sample density and quality, inferred mineral resources were defined. This case history demonstrates that even though the density of drilling might have been high enough to justify a measured resource status, it was considered that the quality of the samples was unsatisfactory, and the resource blocks were down graded to an indicated resource status as a result.

Concluding comments

The above discussion demonstrates that diamond drill core quality can affect all the parameters used to evaluate a mineral deposit, namely, thickness, area, grade and bulk density. It is doubtful whether any other potential error can have such a pervasive affect. One other aspect not yet considered is the impact of core loss on the geological modelling of a deposit. If important structural features are not recognised due to poor recovery in critical areas, then the model applied may be incorrect and hence the resulting block grade model will not reflect the situation in the ground. Non-recognition of such features can also affect estimates of mining recovery and of rock mass stability underground.

In Table 1 (*Checklist of Assessment and Reporting Criteria*) of the 1999 JORC Code and proposed 2003 revision (and similarly in other codes/guidelines)[14,18] the importance of proper logging and core recovery is stressed. The checklist is not prescriptive, but encourages the competent person into reporting matters that might materially affect a reader's understanding or interpretation of the results or estimate being reported. Specifically Table 1 states:

> ***Logging:*** *Whether core or chip samples have been logged to a level of detail to support appropriate mineral resource estimation, mining studies and metallurgical studies. Whether logging is qualitative or quantitative in nature. Core (or costeen, channel, etc.) photography.*
>
> ***Drill sample recovery:*** *Whether core or chip sample recoveries have been properly recorded and results assessed. In particular whether a relationship exists between sample recovery and grade and whether sample bias may have occurred due to preferential loss/gain of fine/coarse material.*

The resource estimator/competent person should seriously consider: (i) use of TCR, SCR and RQD parameters to describe better both core recovery and quality; and (ii) more effectively use this recovery and quality data in the resource estimate. The next step is to consider these values as regionalised variables, leading to block modelling alongside those usually considered in a resource estimate.[3]

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