Geological and Grade Risk at the Golden Gift and Magdala Gold Deposits Stawell, Victoria, Australia

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ABSTRACT

The Golden Gift is a recently discovered deep deposit below the main operating areas of the Stawell Gold Mine. At an early stage of the project, diamond drilling was used to define the mineralisation on sections approximately 100 - 150 m apart. The project economics were sensitive to both grade and tonnage. There were consequently two significant risks on resource quantification:

1. risk on tonnage ('geological risk'); and
2. risk on grade ('grade risk').

The degrees of freedom inherent in the geological model were considered to be potentially high because of wide drill spacing and likely structural complexity. To quantify geological risk three geologists familiar with Stawell mineralisation independently interpreted the deposit. This generated three plausible, different geological volume models.

Conditional simulation was then used to quantify grade risk. Conditional simulation requires the user to define input statistics (histogram and variogram model) and a geological envelope. Based on global mean grade of an ordered set of simulations, 'pessimistic', 'median' and 'optimistic' simulation cases were defined

The result was a 3 x 3 risk matrix with geological risk (the three interpretations) on one axis and grade risk (also three cases) on the other axis. An interesting result was that geological and grade risks were of a similar order of magnitude. Therefore a risk analysis of grade by geostatistical methods within a fixed geological model is of limited value, especially if the drill spacing is wide. After completion of this study, with additional drilling, the geological degrees of freedom at Golden Gift reduced substantially. A second Golden Gift risk study used a refined geological model to build a set of simulations to be used in preliminary mine design.

A third simulation study in the deeper parts of the Magdala ore deposit, a well-drilled part of the mine with production history, demonstrates that the geostatistical simulation method used at Golden Gift is a robust and useful tool to quantify grade risk.

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INTRODUCTION

This paper presents a case study that quantifies both geological risk and grade risk in an underground gold mine at Stawell in western Victoria. In recent years, geostatistical simulation has been used to quantify grade risk at numerous mines and a case study of this type of application is presented here. Whilst simulation is an excellent tool for risk analysis of grade, in the usual approaches taken it relies on a fixed geological interpretation. In this paper it is also shown that, at early stages of a project, there can be a high degree of risk in geological interpretation. This 'geological risk' is usual in emerging projects and we propose a simple approach for quantifying it.

The discovery of Golden Gift deposit beneath the Magdala orebody, which is the main economic deposit at Stawell, presented the operators (Stawell Gold Mines, or 'SGM') with several dilemmas. With the cost of drilling 1000 m+ holes prohibitive and limited suitable positions to drill from underground, SGM wanted to assess the size and tenor of the Golden Gift deposit at an early stage prior to further commitment to drill platforms. In addition, the main resource risks at this phase of the project needed a quantified characterisation. To complicate matters, the geological setting of the Golden Gift, whilst broadly analogous to the Magdala orebody, has a high degree of structural dislocation. It was apparent that the degrees of freedom when interpreting ore positions meant there could be many valid interpretations that would provide very different results when estimating gold resources.

There are dangers in using geostatistical simulation at very early stages of a project. The stationarity assumptions required for conditional simulation ('CS') are much stronger than for traditional linear estimates (eg ordinary kriging). In this study the method is shown to be a valid tool to assess the tenor of the orebody, and also to characterise grade risk by using additional information from Golden Gift and through another study in the very well informed parts of Magdala.

This paper assumes the reader has a basic understanding of linear and the concepts of non-linear geostatistics. Armstrong (1998), Goovaerts (1997), Isaaks and Srivastava (1989) provide good background reading in linear geostatistics. Vann *et al* (2002) summarise geostatistical simulation with more detailed material given in Lantuejoul (2002) and Chiles and Delfiner (1999).

GEOLOGY

The Stawell Goldfield is located within a package of deformed Cambrian turbidite sediments that are fault-bounded against a deformed sequence of metabasalts within the Stawell Zone of the Lachlan Fold Belt (Gane and Wilson, 1999).

Magdala

East-west compression of the Lachlan Fold Belt during the Ordovician against the pre-Cambrian Adelaide Fold Belt has uplifted a sequence of multiple basalt flows and sea floor volcanogenic sediments from the base of the stratigraphic pile (Fredericksen and Gane, 1998).

Ore from the Magdala mine is produced from a series of subparallel lodes hosted by faults and shear zones on the western flank of a large basalt antiform 'the Magdala Anticline' (Figure 1).

The most important lodes, Central lode and the Basalt Contact lodes, are intimately associated with an intensely deformed package of volcanogenic sedimentary rocks. Mineralisation styles can be broadly described as follows:

- *Basalt contact* mineralisation occurs in chloritic sediments overlying the basalt. Gold is located in narrow west-dipping shear-hosted veins and vein arrays dominated by quartz-pyrrhotite-arsenopyrite-pyrite veining and vein selvedges. Gold occurs as free gold in quartz and sulfides or as associations with sulfides;
- *Central lode* mineralisation occurs in complex shear-hosted veins to the west of, and sometimes adjacent to, the basalt. Mineralisation is dominated by quartz-pyrite-arsenopyrite formed in a reverse fault system with dextral strike-slip sense of movement (Miller *et al*, 2001). Gold occurs as free gold in quartz and as associations with sulfides; and
- *Stockwork* mineralisation is developed in quartz and sulfide vein arrays associated with dilatant zones adjacent to flexures in basalt contacts or major shear zones such as Central Lode. Gold occurs as free gold in quartz, sulfides or chloritic sediments and as associations with sulfide assemblages.

Ore shoots developed within the Magdala Lodes generally plunge steeply north, but are constrained within a moderate northerly plunging corridor bounded by the Scotchmans Fault and the South Fault (Figure 2). It is within this corridor that all recent production activity has been focussed.

Golden gift

Since the beginning of the modern era of mining at Stawell several generations of exploration driven by structural modelling, investigated the possibility that the South Fault truncated a much larger Stawell orebody and that the remainder of the Magdala system (lower block) lay unseen either to the east, west, or at depth.

Early drilling tested the area under the South Fault at the south end of the mine, without success. It was concluded that the lower block either did not exist or lay at a greater depth.

Detailed structural studies on the underground South Fault exposures by University of Melbourne researchers during 1998 - 1999 indicated that the South Fault and related structures evolved from a north over south (along strike) movement sense to a northeast over southwest (across strike) movement sense.

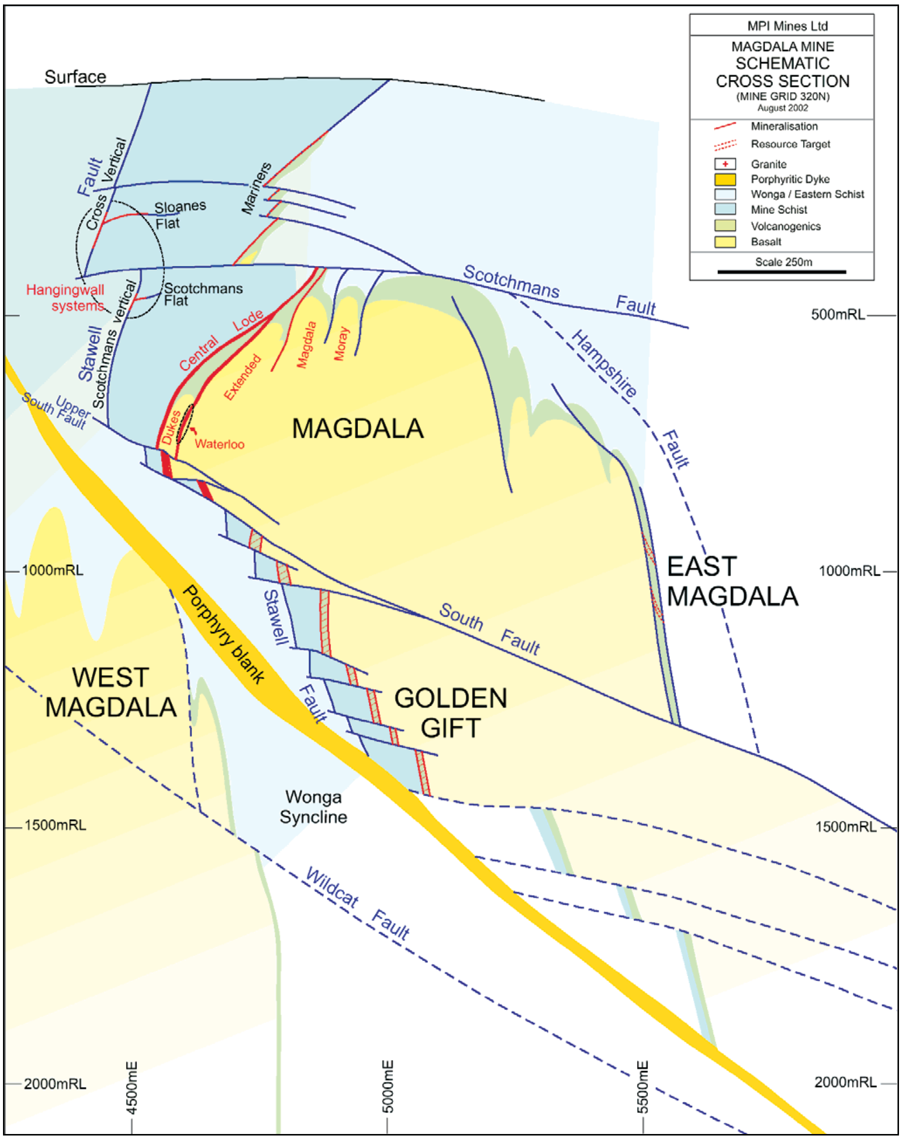

FIG 1 - Schematic cross-section of Stawell geology and orebody locations.

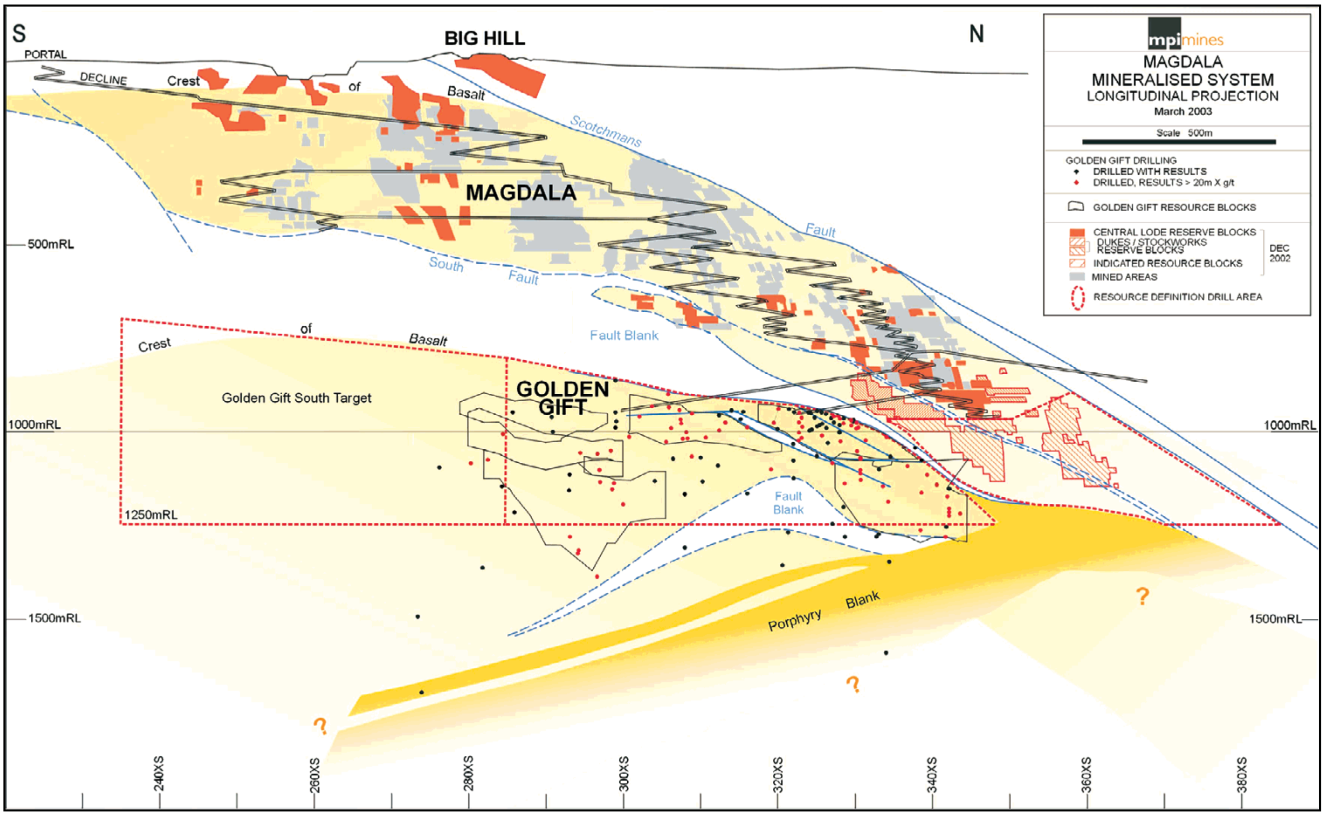

FIG 2 - Longitudinal section of the Magdala and Golden Gift mineralised system.

Depending on the relative degrees of movement, it was concluded that the deeper basalt (lower block) should lie underneath, and to the north of the known Magdala system.

Magnetic modelling, combined with reconstruction of the movement history of the fault, allowed a best case scenario for the position of the lower block to be constructed. Diamond drilling to test the concept commenced in June 1999 with success in the second hole of the program. As of mid-2003, drilling had outlined a zone of mineralisation with a strike length of more than 1500 m and a vertical extent of about 350 m.

Current assessments of the geology show the same stratigraphic relationships at Golden Gift as established for the Magdala orebody, and the same range of mineralisation styles as previously described. It is apparent from the drilling completed to date that there is a significant amount of structural dislocation, not unlike areas of the Magdala orebody previously mined or being mined currently. Detailed metallurgical testing has also been completed which also indicates similarity of the two deposits.

GEOLOGICAL RISK

Early stage geological interpretations from different geologists

Most mining professionals know that getting more than one geologist to interpret an orebody is inviting, at best, a lively discussion. These discussions usually involve a lot of 'arm waving' and postulating of various geological models. The main reason for such debate and disagreement is the very limited amount of information available at the time of interpretation.

Geologists at Stawell were faced with exactly this 'lack of information' dilemma. In February 2002, there were only 28 mineralised holes in the Golden Gift. In an attempt to measure the risk on the geological model, three geologists undertook independent interpretations of geology, focussing on location of ore horizons and structural dislocations. The geologists were:

A. The exploration geologist involved in the discovery of the orebody;

B. The resource geologist with several years practice at estimation of resources at SGM; and

C. The mine geologist who has been trying to work out the details of the Magdala orebody for several years.

Each geologist did a three-dimensional (3D) interpretation of the orebody using identical information (ie the same holes, logging and assays). Figure 3 shows a cross-section with the three different geological interpretations. Whilst the local differences in interpretations may initially appear surprising, given the experience of the geologists, it is clear that there are significant degrees of freedom with such sparse drilling information. Globally the impact each interpretation has on the tonnes is quite significant. Table 1 presents the differences in tonnage between the three cases relative to the middle or median case. Note tonnages are calculated from the total volumes of each of the modelled solids. The differences in tonnage could be even more striking if we apply a cut-off.

TABLE 1

Relative global tonnages for the three different interpretations expressed as a percentage of case B.

Geologist	Comparison to median
A	125%
B	100%
C	79%

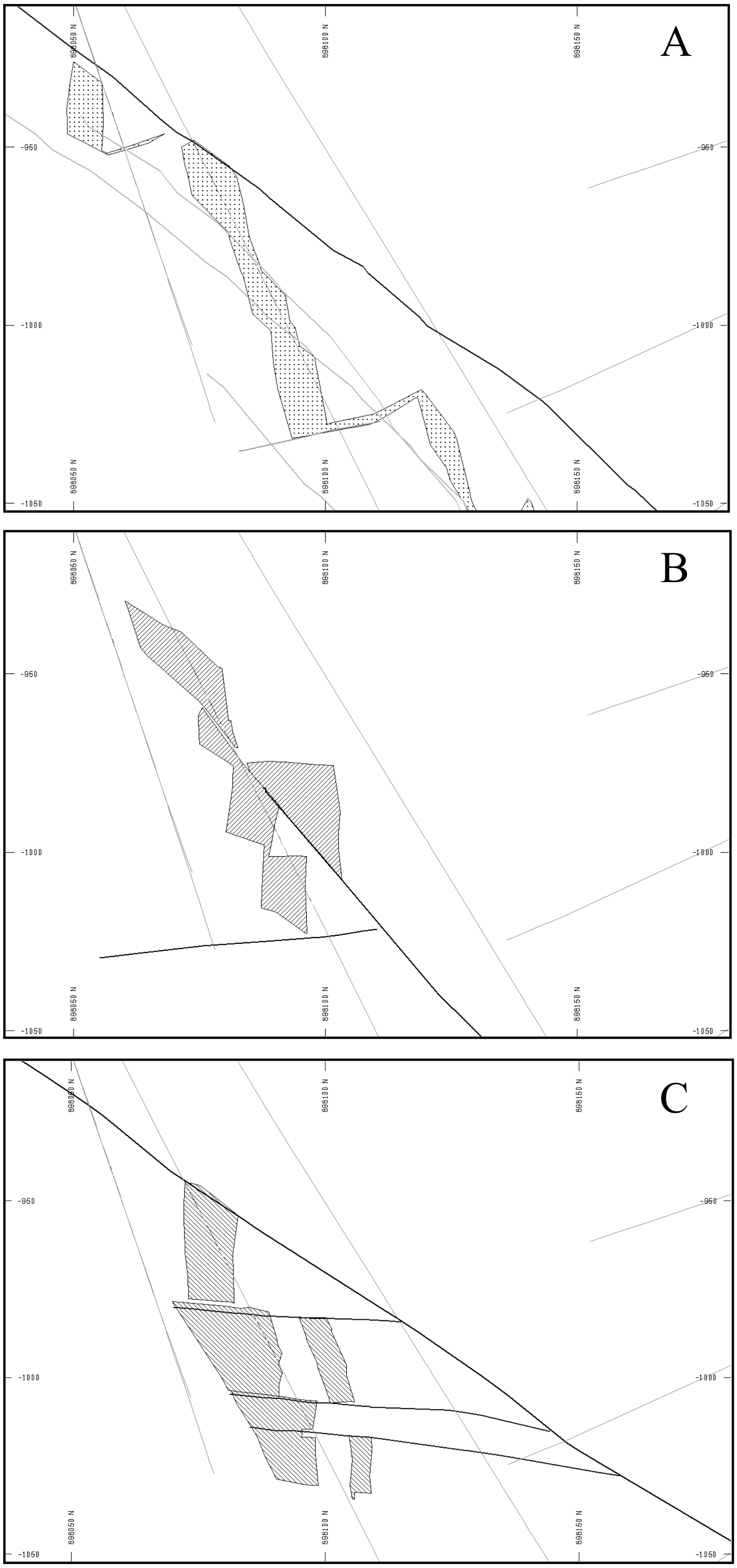

FIG 3 - Cross-section of geological interpretations from geologist A, B and C. Mineralised zones are hatched, faults black and drill holes grey.

The exercise of comparing three 'plausible' interpretations demonstrates there is both local and global *geological* risk associated with estimating the resource at this early stage, which in this case has been quantified. Globally the volume estimated could be plus or minus 20 - 25 per cent.

GRADE RISK

Having established that there is risk in the interpretation, it remains to assess the risk on the grade at Golden Gift. One way to quantify grade risk is via geostatistical simulation. Geostatistical simulation has become a powerful tool in mining in a wide variety of applications.

Geostatistical simulation – A brief overview

There are now many publications dealing with various aspects of conditional simulation. Chiles and Delfiner (1999) and Goovaerts (1997) provide good introductions and the more mathematically inclined can refer to Lantuejoul (2001) for technical descriptions of the methods. An overview from Vann *et al* (2002) is given below.

Geostatistical simulation is a spatial extension of the concept of Monte Carlo simulation. In addition to reproducing the data histogram, geostatistical simulations also honour the spatial variability of data, usually characterised by a variogram model. If the simulations also honour the data themselves, they are said to be 'conditional simulations'. Conditional simulations can be regarded as plausible images of the mineralisation at a fine scale. In a sense, simulations are an attempt at 'sampling the unknown' using constraints, eg statistical moments imposed by the data. Thus, in simulation, the requirements of stationarity are stricter than for linear geostatistics (for example, kriging). With data sets based on sparse drilling, as at Golden Gift, there is inherently less confidence in the statistical moments employed; ie we are less sure that we have the right characterisation of the variance and the variogram as the level of data decreases.

Geostatistical simulation is also much more computationally demanding than geostatistical estimation. However, the exponential increase in computer processing speed, memory and data storage capacity have brought these tools into wide operational use in the mining industry over the past decade. We can generate many (in theory an infinite number) of simulated images. The validity of any subsequent use of the simulations for risk characterisation will be heavily dependent on how well our set of simulations samples the 'space of uncertainty'.

For the Golden Gift the two most frequently used methods for conditional simulation were considered: Turning Bands (TB) and Sequential Gaussian Simulation (SGS).

INITIAL CASE ASSESSMENT

Processes

A test study was undertaken to see if the above grade simulation project was feasible. The style of mineralisation and relatively preliminary and poorly constrained domaining precluded a two-dimensional approach. Thus for a 3D study, the main concern was whether the conditional simulation algorithms tested would provide acceptable outputs using the dataset provided. Standard data analysis was undertaken reviewing composite length, statistical characterisation, spatial homogeneity (clustering) and top cuts (if necessary). One metre fixed length composites were chosen. Gaussian transforms were run (a requisite for both SGS and TB). No weights were applied to the transform because choosing a declustering weight was nothing more than arbitrary with only 28 holes.

Determining a variogram model with only 28 holes and 645 composites was problematic. A variogram model was chosen that was based on one used in the Magdala Upper South Fault Block which is currently being mined. The original model was simply scaled to the variance of the Golden Gift data. At that early stage of exploration of Golden Gift, this assumption was considered geologically reasonable by Stawell geologists.

In the plane that approximates the lateral extents of the domain, an isotropic model chosen with a 15 per cent relative nugget effect and a 40 m range. What this means, practically, is that samples greater than 40 m apart are spatially uncorrelated. The implication of this is discussed further below. The variogram model used is tabulated in Table 2.

TABLE 2

Variogram model parameters for Golden Gift early stage variogram.

	Nugget	Structure 1 (Spherical)	Structure 2 (Spherical)
Sill	5.30	10.60	22.00
Proportion of total sill	14%	28%	58%
Range D1 (m)		15	40
(Az 135°, Dip 0°)			
Range D2 (m)		15	40
(Az 135°, Dip 90°)			
Range D3 (m)		5	15
(Az 45°, Dip 0°)			

Conditional simulation by both methods tested (SGS and TB) requires a search neighbourhood because kriging steps are involved. Search neighbourhoods were tested and defined quantitatively. Vann *et al* (2003, this volume) describe the methodology for such tests.

Initially simulations were run on a grid that was rotated 45° (a close approximation of the lateral orientation of the domain) with a node spacing of 1 × 2.5 × 2.5 m. For each method at least 150 realisations were generated for testing.

Turning Bands

Turning Bands (TB) was the first large-scale geostatistical simulation algorithm implemented (Journel, 1974; Mantoglou and Wilson, 1982). The method works by simulating one-dimensional processes on lines regularly spaced in 3D. The one-dimensional simulations are averaged to yield the simulated values with the required 3D covariance. Conditioning is obtained through a separate, subsequent kriging step.

The TB realisations performed quite well in that they reproduced input statistics adequately. The mean of 150 realisations was well within the range of values derived in the declustering tests, as was the variance. Histograms of different realisations also replicated the input raw data histogram quite well with exceptions in the more extreme realisations (in a global mean sense). Likewise, experimental variograms generated from a sample of the realisations show the spatial variability was being replicated well.

Sequential Gaussian Simulation

Sequential Gaussian Simulation (SGS) is an efficient method also widely used in the mining industry. The algorithm, in very simple terms, defines a random path through all grid nodes (points). The points in the path are progressively simulated. Each new simulated value is then added to the conditioning data and the next point in the path is simulated (and so on).

Compared to Turning Bands, judged in terms of adequacy of replication of input histogram and variogram, SGS was deemed not to have performed as well on the Golden Gift although the differences were not highly significant. Turning Bands simulations were used for this study.

Post processing

Once the 150 realisations had been produced and tested at the point level (eg 1 × 2.5 × 2.5 m), each realisation was re-blocked to the dimensions of the smallest reasonable mining block. At Magdala, 5 × 15 × 20 m mining blocks were used for planning, so this was initially applied to Golden Gift. The re-blocking was performed by averaging all the simulated nodes in each 5 × 15 × 20 m block. Dilution was applied in cases where not all points in a 5 × 15 × 20 m block had been simulated (due to geometry). The block was diluted by adding the un-simulated nodes at a zero grade. This step incorporated a level of conservatism to the process. The resulting blocks provided a basis for examining results and possibly early stage mining studies.

Choosing which cases to use for risk assessment

At this point we had a large set of simulated models of the Golden Gift based on one fixed domain provided by 'Geologist B'. Clearly it is not practical to run mining studies on 150 (× 3 interpretations = 450) realisations. We decided that three realisations should be chosen for each domaining case. The selection process decided upon was to globally rank all realisations by mean grade:

- select five realisations around the 5th percentile ('pessimistic cases');
- select five realisations around the 50th percentile or median ('median cases');
- select five realisations around the 95th percentile ('optimistic cases'); and
- run checks on each of the five realisations in the groups and choose one that appears the most reasonable, ie the histogram, variogram, conditioning and 'geological feel' are all sensible.

The optimistic and pessimistic cases can be viewed as 90 per cent confidence limits for a deposit, given that the assumptions about the input histogram, variogram and geological models are reasonable. If these assumptions are reasonable it can be concluded that it is unlikely that the deposit, in reality, lies outside the 90 per cent limits.

Results from early stages

The objective of the early study was to assess whether simulation produced sensible results on which a risk analysis could be run and the scale of the grade risk ie pessimistic versus median versus optimistic cases.

Using the median case as the base, results showed that in a global sense:

- the contained metal above cut-off for the pessimistic case was ~60 per cent of the median case; and
- for the optimistic case contained metal was ~170 per cent of the median case.

Whilst this range is extremely large, it is not unexpected. At that time the average data spacing was wider than the range of the variogram used. Consequently there were large parts of volume being simulated that were not well conditioned and were relying entirely on the histogram to generate grades in those regions. Thus the spread of resulting simulations was very wide.

As data density increases, which results in simulations becoming more conditioned, the difference between the optimistic and pessimistic cases is expected to decrease.

Risk matrix

Bearing in mind that the above simulations were run on a single fixed geological interpretation, a risk matrix was built combining geological and grade risk. Table 3 shows that at the early stage there are risks associated with both the geological interpretation and the grade. Clearly, in this case, grade risk is higher than geological risk. The most pessimistic case is 68 per cent lower than the median and the most optimistic result is 112 per cent above the median. The conclusion was the project was economically interesting and further drill testing warranted.

TABLE 3

Relative difference in metal above cut-off compared to median case with Geologist B.

	Geologist A (optimistic)	Geologist B (median)	Geologist C (pessimistic)
Optimistic simulation	212%	170%	134%
Median simulation	125%	100%	79%
Pessimistic simulation	50%	40%	32%

IMPACT OF ADDITIONAL INFORMATION

By October 2002, a further 33 holes had been drilled into the Golden Gift mineralisation. Thus a total of 61 holes with 1306 composites within mineralised domains were available for estimation.

Diminished geological risk

With an additional year of drilling and the resultant improved knowledge and understanding added to the geological model, the degrees of freedom from the geological interpretation were considered to be much less. In particular, detailed analysis of orientated core helped resolve structural controls. A single revised geological interpretation was made and subsequent geological domains were built by Stawell geologists. Six geological sub-domains were identified based on location and orientation. All domains still combined the different lodes, eg Central, Basalt Contact, etc.

Diminished grade risk

Using the additional drilling information, a new set of conditional simulations was run. The same processes were followed as the initial simulation exercise except that the Gaussian transformations and variogram modelling processes were modified to account for the additional data. With the additional data, cell declustering tests showed there was a difference between declustered and raw statistics. Declustering weights were therefore applied to the Gaussian transforms. The additional data also meant meaningful variograms were now calculated and modelled. A single variogram model was built for use in all of the six domains using all the data available. In the end, however, the variogram models did not alter appreciably from those used in the previous exercise.

Turning Bands was again selected as the method and used to generate another set of conditional simulations in each domain. These were checked and re-blocked to mining sized blocks with dilution incorporated as per the previous methodology. It was decided to combine the different (independent) realisations for each domain based arbitrarily on the simulation number. The combined and re-blocked models were used for ranking and selection purposes. Three cases were chosen in a similar fashion to the method utilised in the original study.

Updated risk matrix

With the geological interpretation now effectively fixed, only the grade variation remained in the risk matrix. Table 4 shows results in terms of metal content for the last resource estimate in October 2002. Compared to the median case, now the pessimistic case is only 70 per cent of the median and the optimistic case 146 per cent of the median. This represents a very significant reduction in risk from the previous exercise where the range went from 31 per cent of the median to 212 per cent.

TABLE 4

Variance of optimistic and pessimistic case in terms of global metal from median case in Golden Gift with additional information.

Case	Comparison to median
Optimistic	146%
Median	100%
Pessimistic	70%

Using the results

The pessimistic, median and optimistic cases were used to look at some preliminary mine designs in order to assess the viability of the project, examine scheduling issues and evaluate financial outcomes. Whilst the individual realisations are useful for very preliminary design work, they are not at all suitable inputs to detailed mine design. In any individual realisation there may be very significant local deviations between the true grade and the simulated grade, especially given the drill spacing is about the same as the range of the variogram. This point is reinforced below.

APPLYING CONDITIONAL SIMULATION TO MAGDALA

Compared to the Golden Gift, the Magdala orebody has a high density drill spacing. The nominal diamond drill spacing is in the order of 15 m × 15 m throughout the lodes. Geologists have been using this data to estimate resources using 3D ordinary kriging.

An exercise was run to simulate in the well-drilled areas and the results assessed in comparison to the kriged estimate to characterise the risk associated with that estimate. For this study the individual lodes were split to form separate domains.

Again a large set of simulations was built using the same methodology as the Golden Gift study. The big difference for this study was the spread of results (see Table 5). Compared to the median case, the metal in the optimistic case was 108 per cent and the pessimistic case 95 per cent.

TABLE 5

Variance of optimistic and pessimistic case in terms of global metal from median case in Magdala (well-informed areas).

Case	Comparison to median
Optimistic	108%
Median	100%
Pessimistic	95%

Reconciling against the resource estimate

A previously mined area between the 881 and 806 levels was used to compare:

1. the ordinary kriged resource estimate;
2. the average of all simulations;
3. the median case simulation chosen globally; and
4. the local median case.

This was done by taking the global average of all the estimated grades in the volume, the global average of all grades for realisation No 1 through to 150. The volume chosen represents about one year's production and 20 per cent of the total simulated volume.

As expected, the average of all the simulations is very similar to a linear resource estimate using the same data (Table 6). The local median case is also within one per cent of the estimate in terms of metal content. What is notable is that the median case chosen globally has the second-highest metal content out of all realisations in the small (local) volume being reconciled. This reinforced our previous warnings above highlighting the dangers of using individual simulations for any detailed mining analysis, eg stope design. The spread of results is displayed in Figure 4.

TABLE 6

Comparison of results between estimate and simulations.

881 Block	Tonnes (*1000)	Grade (g/t Au)	Metal (ounces *1000)
Estimate	423	7.3	99
Average of all realisations	420	7.3	98
Global median	451	7.6	111
Local median (for 881)	418	7.3	98

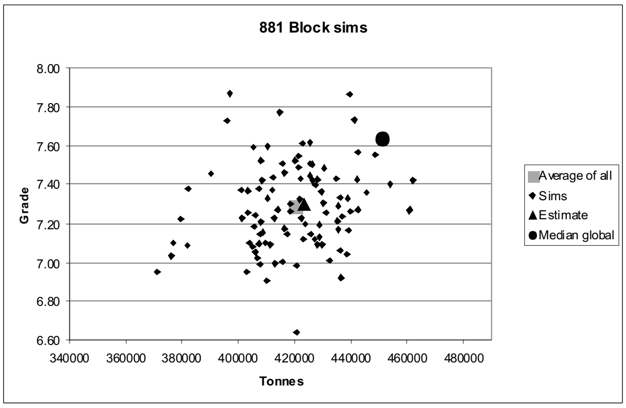

FIG 4 - Comparison of individual realisations, average of all simulations, global median simulation and linear estimate for 881 block.

CONCLUSIONS

At the early stages of a project like the Golden Gift there are two resource risks that can and should be quantified: geological risk and grade risk. In our case study we demonstrated that whilst the risk derived from geological interpretation is not as high as grade risk, it is still very significant.

As projects progress and additional drilling information and geological understanding is acquired, the degrees of freedom on both grade and geological interpretation will diminish. However,

TABLE 7

Comparison of risk profiles for early stage Golden Gift (geology and grade), late stage Golden Gift and Magdala.

Case	Early Stage Golden Gift			Late Stage Gift	Magdala
	Geology	Grade	Combined	Grade	Grade
Optimistic simulation	125%	170%	212%	146%	108%
Median simulation	100%	100%	100%	100%	100%
Pessimistic simulation	78%	40%	32%	70%	95%

geological risk at early stages could easily have a dramatic impact on financial outcomes. Clearly the degrees of freedom in a geological interpretation cannot be ignored and where possible they should be quantified. In practice, conditional simulation studies are often performed for early stage risk analysis using a single geological model. This assessment only of grade risk will generally understate risk on metal and in some cases the understatement could be serious.

At the mining stage, when the data density is maximised, we have shown there are still risks on grade, albeit much reduced. Table 7 summarises the reducing risk profile with additional information from early stages of Golden Gift to advanced stages of Magdala. Even though there are considerably less degrees of freedom in the geological interpretations at later stages, geological risk, though diminished, is not negligible.

Finally, the important conclusion is drawn that geostatistical simulation tools, in isolation, may under-call the risk in early stage projects. Part of the solution is the ensure that due consideration is given to variability in geological risk. However, the additional aspect of risk not considered in this paper is on the inputs themselves, ie the statistical moments (variogram and histogram). Further work could be directed at assessing the impact of uncertainty on the variogram and histogram on the spread of possible outcomes.

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