

Testing new estimation techniques – rank and replace: a stockwork case study

Danny Kentwell and Dave Finn

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Abstract

Experience has shown that the E-Type multiple indicator kriging (MIK) estimation technique often works well for resource estimation in stockwork mineralisation that contains a mixture of high and low-grade mineralisation types that are difficult or impossible to separate spatially. E-Type MIK, like ordinary kriging (OK) is a smoothing estimator and where data is sparse can result in estimates of grade tonnage curves that do not reflect the true block variability at selective mining unit (SMU) scale. The rank and replace (RR) estimation methodology is designed to reproduce both local block accuracy and true block variability at SMU scale and has shown good results when used with highly skewed unimodal diffusive style mineralisation. This paper examines the use of RR with mosaic style mineralisation typically found in stockworks via a case study using real data from Newcrest's Telfer West Dome deposit. Resource level estimation results for ordinary kriging (OK), E-Type MIK and RR are compared to close spaced grade control models as the reference reality.

Results show that stationarity requirements and declustering can severely impact on the usefulness of the rank and replace technique and that it should only be used where trends are not too strong and data are relatively uniformly spaced. This does not rule out its application to stockwork or mosaic style deposits. However, in this case, the presence of trends and different data densities requires the non-stationary domain to be further broken down into sub domains for the RR technique to be effective.

INTRODUCTION

When estimating block grades for mining purposes, the currently available methods allow us to maximise the accuracy of either global grade and tonnage curve prediction (simulation, local uniform conditioning (LUC), localised MIK with a change of support) or maximise the accuracy of local block selection (ordinary kriging with optimal search, E-Type MIK with optimal searches) but not both at once. Locally accurate block estimates provide the best result during actual selection and mining but can give highly distorted global grades and tonnages at cut-offs above zero when estimating from sparse data. Globally accurate block estimates provide good prediction of grade and tonnage curves but can perform badly during actual selection giving much higher misclassification rates leading to serious degradation of value of the material selected for processing. These statements hold true in varying degrees for all scales and combinations of sample spacing and block size.

The RR method (Kentwell, 2017) puts forward an estimation methodology that retains the properties of accurate global estimation whilst simultaneously approaching maximum local accuracy. The process is a simple application of rank and replace, combining two estimates, one that targets local block accuracy and one that targets actual block variability. In its broadest sense, any method targeting local accuracy coupled with any method targeting true block variability can be used. The method has much in common with LUC but assigns individual block locations globally rather than per panel.

The implementation of RR presented here utilises an ordinary kriged SMU estimate with the search neighbourhood and sample restriction parameters optimised for a balance between maximum regression slope and minimum negative weights for the locally accurate estimate. The true variability SMU distribution is, in this study, estimated via a discrete Gaussian change of support.

This study examines a single low-grade stockwork domain (domain 100) with a declustered average grade of 0.22 Au ppm from Newcrest's Telfer West Dome Resource. There are two data sets available. The resource development (RESDEV) drilling and the blasthole grade control (GC) drilling. The GC drilling covers only a small, higher grade, part of the full domain 100 and has a declustered average of 0.46 Au ppm.

The 100 domain was chosen because it is a difficult domain to estimate for several reasons. Firstly, the geology is such that isolated low continuity high-grade mineralisation co-exists with low-grade higher continuity

mineralisation at a scale that cannot be modelled or domained separately. Secondly there are significant grade trends in all orientations. Thirdly there is a huge variation in the drill spacing over the domain. Newcrest have previously used E-Type MIK to estimate the full domain 100 as a whole.

THE DEPOSIT

Stratigraphy

The geology of the Telfer Mine area consists of a late Proterozoic sequence of marine sediments known as the Lamil Group that have been weakly metamorphosed, structurally deformed by folding and faulting and locally intruded by granites.

Within the Telfer District the Lamil Group stratigraphy has been divided into five formations that are subdivided into members. Gold and copper mineralisation at Telfer consists of strataform reefs and stock-works hosted by siliciclastic to carbonate sedimentary rocks of the Malu (MFM) and Telfer (TFM) Formations. The detailed members used during resource modelling are:

- Camp Sandstone – 20 m thick. Medium to coarse grained sandstone at the contact with the Puntapunta Formation.
- Outer Siltstone (OSM) – 500 m thick. Well stratified, thinly bedded argillaceous, calcareous and minor carbonaceous siltstones with interbedded sandstone. This is the host to the E-Reef mineralisation horizons. The E-Reef horizons typically sit at 15 m, 25 m, 35 m, 45 m, 55 m, and 60 m above the Rim Sandstone contact.
- Rim Sandstone (RSM) – 25 m thick. Massive coarse to medium grained, interbedded quartz sandstone and argillaceous siltstone. This is the host to localised Rim Pod mineralisation that is characterised by disseminated pyrite, associated sericite alteration and stockwork quartz veining.
- Median Sandstone (MSM) – 35 m thick. Poorly stratified, very thickly bedded, fine grained, and well sorted quartz sandstone with minor siltstone interbeds. Mineralisation typically occurs as small reefs and localised pods.
- Middle Vale Siltstone (MVS) – 10 m thick. Fine grained and thinly bedded argillaceous siltstone, mudstone, and claystone with minor interbedded sandstone. This is the host to the Middle Vale Reef (MVR).
- Footwall Sandstone (FSM) – 25 m thick. Commonly graded, fine grained interbedded sandstone and siltstone. This hosts extensive footwall stockwork and disseminated pyrite mineralisation. Typically the mineralisation is associated with sericite alteration.
- Lower Vale Siltstone (LVS) – 3 m thick. Fine grained and thinly bedded argillaceous siltstone, mudstone, and claystone with minor interbedded sandstone at the contact with the Malu Formation. This is the host to localised reef mineralisation.

Structure

Dome structures

The topography at the Telfer Mine site is dominated by two large scale asymmetric dome structures with steep west dipping axial planes. Main Dome is located in the south-east portion of the mine and is exposed over a strike distance of 3 km north–south and 2 km east–west before plunging under late transported cover. West Dome (WD) forms the topographical high in the north-west quadrant of the mine and has similar dimensions to Main Dome. Both fold structures have shallow to moderately dipping western limbs and moderate to steep dipping eastern limbs.

North–south monoclines-anticlines

A total of five monocline-anticline structures have been mapped in surface and underground exposures and logged in drill holes in Main Dome and West Dome. These strike north–south and are typically 1 km in strike length and 50 m to 200 m wide. They form double plunging structures with axial planes orientated 35° to 50° to the west. In all cases at Telfer, monocline-anticline structures commence and terminate as open fold structures, whilst the central portions of the monocline-anticlines typically have steep east limbs which in some areas are overturned (hence local reference to the term monocline).

Fault structures

Several fault sets have been identified by logging and mapping and consequent interpretation. They include:

- west shallow to moderate dipping fault systems, semi-parallel to the monocline-anticline fold structure

- north-west moderate dipping fault set
- south-west moderate dipping fault set
- north-east striking fault set (Graben Fault set)
- east–west striking near vertical fracture set (Leader Hill vein set).

Stockwork mineralisation

Stockwork mineralisation is characterised by narrow, often discontinuous veins that cross-cut stratigraphy. Large domains of stockwork mineralisation have been defined in the open pits and also within the Telfer Deeps resource. Individual stockwork domains within the open pit resource have the following broad characteristics:

- broadly discordant to lithological boundaries, although some stratigraphic units have more abundant stockworks than others
- laterally extensive, between 0.1–1.5 km scale
- moderate to high relative nugget effect
- geometry of the stockwork domains related to structure
- and stratigraphy
- gold grade within the broad stockwork domains is typically around 1 g/t Au, but the grade of the vein material alone can be of a similar magnitude to the narrow vein reef material, ~ 5 g/t Au to ~ 50 g/t Au
- stockwork mineralisation also includes areas of breccia formation; the mineralisation within these breccia zones is similar to that in the narrow vein reefs, dominated by quartz-carbonate-sulfides/oxides assemblages.

ESTIMATION

A single stockwork domain (100) was used as to test the rank and replace method. Domain 100 sits in the Telfer formation and consists of the RSM and MSM lithologies and contains oxide, transition and fresh material. This domain is a large, non-stationary (contains a trend) domain with widely varying drill spacing. A small part of domain 100 has been grade control drilled mostly on a 8 m × 7 m staggered pattern. This small part of domain will be referred to as the 100 sub domain. Compositing for the grade control data is 16 m downhole. The grade control volume is mainly in transition material with a small amount of oxide material.

The initial estimate using E-type MIK did not differentiate between oxidisation type and used all RESDEV data within the domain for indicator variography and estimation. Resource estimation drilling is between 10 m by 10 m in the upper parts and 200 m by 200 m in the lower parts of domain 100 and consists of both reverse circulation (RC) and diamond core (DD) drilling.

Figures 1 and 2 shows the plan and cross-section views of the data used for the study. Note the sparsity of data at the extremes. Figure 3 shows the raw and log scale declustered Au RESDEV histograms. The data is not noticeably multimodal but that does not rule out either a MIK or rank and replace approach to estimation.

The resource model

The resource model was initially estimated by Newcrest with E-type MIK together with a check estimate by OK. The block size is 12.5 m × 12.5 m × 12 m.

E-Type MIK

OK is sometimes considered to be suboptimal for estimating highly skewed mineralisation without the incorporation of aggressive top-cuts to avoid the over-representation of the extreme ends of the data distribution. Even then, the grade- tonnage curve can be materially distorted compared to reality.

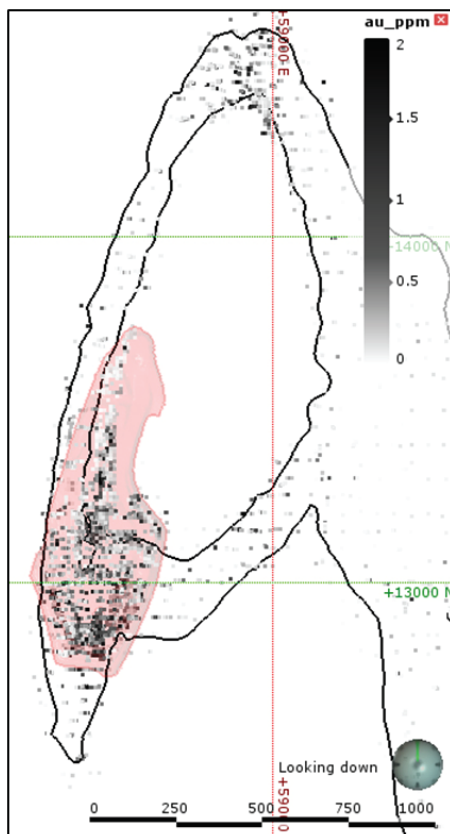


FIG 1 – Grade control model volume within domain 100 resource drilling Au grades, plan view.

In the experience of the authors, E-Type MIK can be better suited for dealing with data sets that display both the highly skewed distributions and non-stationarity.

Although the limited distances typically used for ordinary kriging search neighbourhoods mitigate, to some extent, the problems arising from non-stationarity, variograms modelled from non-stationary domains can have a significantly higher total variance than that within the local search neighbourhoods. Variogram models fitted on the whole domain can have exaggerated ranges and incorrect nugget values as a consequence. By contrast, although indicator variograms still utilise the full domain, the presence of a trend implies some segregation of the high and low-grades to which the indicator variograms should conform better.

E-type MIK is often described as appropriate for mosaic type models, as opposed to diffusion type models. Tests for mosaic model compatibility were completed by looking at variogram/madogram ratio and cross variograms of indicators. The variogram/madogram test showed reasonably constant values with distance suggesting a mosaic model. The indicator cross variograms showed indications of correlation at low lags indicating a diffusive model at distances of around 50 m and up to 100 m.

On the basis of the preceding factors, it was decided to use E-Type MIK to estimate the stockwork domain. The E-type MIK results will be referred to in the remainder of this paper as MIK RESDEV.

E-Type MIK does not involve a change of support but estimates a set of proportions/probabilities at set indicator thresholds that form set of points on a conditional distribution function for each SMU block. The kriging of the indicators thereby results in a discrete distribution which is converted to a continuous distribution by interpolating between the discrete probabilities. For the middle classes (first cut-off to the last cut-off) linear interpolation is deemed sufficient. The lower and upper tails are treated differently. Linear interpolation between 0 to the first cut-off (lower tail), and the last cut-off to the highest composite value (upper tail) is not appropriate because the distribution is more erratic. The tails are modelled by fitting power or hyperbolic models.

Ordinary kriging

OK is the default industry standard estimation method and is the best estimator for final selection where close spaced drilling has been completed. When used with sparse data, compared to the variogram ranges, or in deposits where the nugget effect is 50 per cent or more it will smooth block grades and give models that predict more tonnage and less grade at cut off grades below the mean of the domain being estimated. Smoothing is inherent to OK estimation. There is a trade-off between the quality of local block estimation, as measured by

kriging regression slope or kriging efficiency, and smoothing. The higher the local block estimation quality is, the higher the smoothing and the lower the global grade tonnage curve accuracy is. The OK results will be referred to in the remainder of this paper as OK RESDEV.

The ground truth model

A stockwork only ground truth model (GTM) was constructed by Newcrest using all available close spaced grade control production data. The intent of the GTM modelling exercise was to generate a high-precision reference estimate of mined- to-date materials, defined by a tightly sampled volume using all available blasthole (BH), RC and DD data. The GTM is considered to be an accurate estimate covering a wide range of grades, rock-types and degree of weathering considered to global histograms of two sample populations. BH and RC/ DD were composited to 16 m (12 m bench + 4 m overdrill) in order to compare sample with similar data support compared to full-length BH samples. Any composites touching the MVR high-grade reef were discarded.

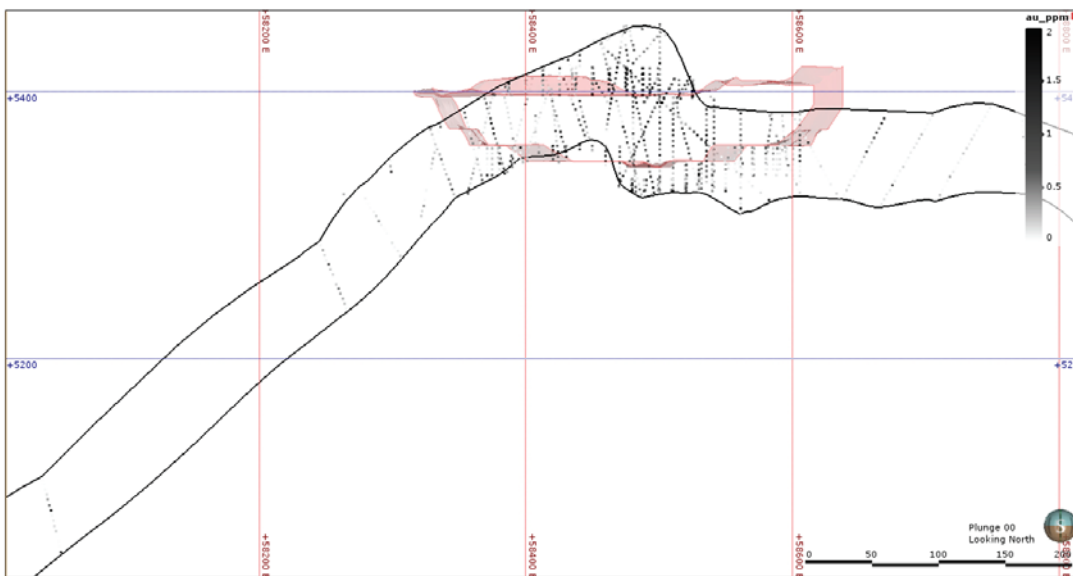


FIG 2 – Grade control model volume within domain 100 resource drilling Au grades, cross-section 12900N.

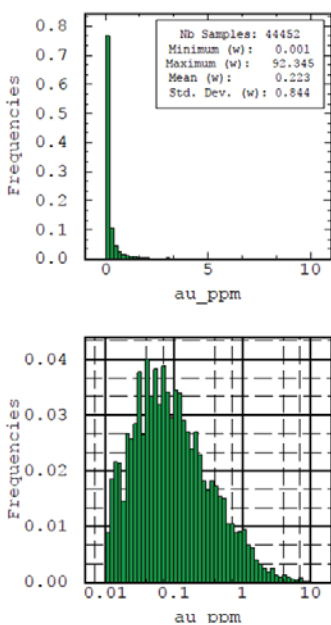


FIG 3 – Raw and log scale declustered Au histograms domain 100.

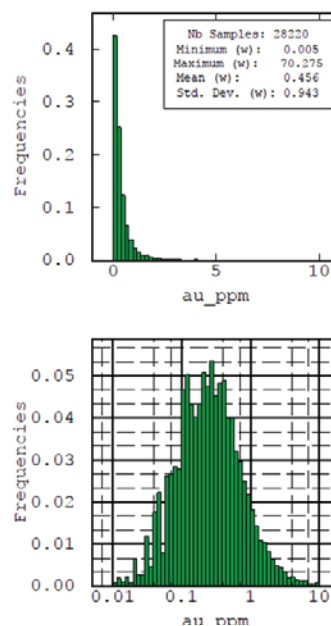


FIG 4 – Raw and log scale declustered GC Au histograms GTM100 sub domain.

Figure 4 shows the raw and log scale declustered Au GC histograms for the GTM100 sub domain.

The GTM was estimated with OK using all available BH, RC and DD 16 m composites within the GTM area. Variogram models were generated by transforming the data to Gaussian space and back-transforming the resulting variogram model to raw space. The local rotation functionality provided by Vulcan was used during OK estimation for both the variogram model and search neighbourhood rotations. The top cuts used for estimation are the same used in the resource model at 25 ppm Au. Search ranges represent 1x the full variogram range with minimum and maximum samples based on kriging neighbourhood analysis, where maximum samples are defined by <2 per cent sum of negative weights and minimum samples based on slope of regression analysis.

The estimation of the GTM100 sub domain is based on 28 220 composites. This compares to 11824 composites from the RESDV drilling within GTM100 sub domain. The GC estimation results will be referred to for the remainder of this be representative of the total West Dome mineralisation. The grade and tonnage curves produced from the Resource model can then be 'benchmarked' against the GTM to determine the most appropriate estimation method for wide spaced data. The GTM covers an area of ~ 300 m x 1000 m x 100 m (X, Y, Z), as shown in Figures 1 and 2.

Comparison between BH and RC/DD

The compatibility between BH, RC and DDH data types within the GTM volume was confirmed using log-probability plots and Q-Q plots which showed no significant differences in the paper as OK GC.

Rank and replace implementation

Background

When estimating block grades for mining purposes, the currently available methods allow us to maximise the accuracy of either global grade and tonnage curve prediction or local block selection but not both at once. The RR method is designed to retain the properties of accurate global estimation whilst simultaneously approaching maximum local accuracy. The process is a simple application of rank and replace, combining two estimates, one that targets local block accuracy and one that targets actual block variability.

Some other methods of smoothing reduction and or correction that have been proposed are (Journel, Kyriakidis and Mao, 2000) using spectral methods and (Richmond, Gaze and Horton, 2009) using an affine correction. Topical papers around the balance between the reproduction of global variability and the reproduction of local block accuracy required for different stages of a project are (Krige, 1951, 1994, 1996; Isaaks, 2005).

It was shown in (Kentwell, 2017) that for a highly skewed Au deposit with good stationarity within the domain the block RR estimate reproduces (the best estimate from available data of) the true block variability globally as well as local selectivity that is very close to that obtainable by OK.

Hence, in the mining context, the method produces a block model that can be used for mine planning purposes that has (the best estimate from available data of) the actual global block grade, tonnage and conventional profit curves as well as (the best estimate from available data of) local block accuracy.

Underlying the RR estimate is conventional ordinary kriging (OK) with an optimised search neighbourhood for the specified block size designed to maximise local block accuracy. The OK block grades are then ranked in grade order. A second estimate, using any method that targets true block variability (global change of support, simulation, degraded neighbourhood kriging etc), is made and the block grades also ranked. The grades from the second estimate are then assigned to the locations defined by the OK estimate by rank order. This happens to be a direct generalisation of the LUC method proposed by Abzalov, (2006).

The RR estimate, as implemented in this study, is derived from a global change of support. The individual ranked block grades were calculated by the following procedure:

- Calculate the block histogram via Gaussian anamorphosis and global change of support using the RESDEV samples and the variogram.
- Report the tonnage curve at a large number (5000) of evenly spaced cut offs across the full range of grades. In this case 0.05 ppm increments were used.
- Export the cut offs and corresponding tonnages to a curve fitting software and fit the data. In this case a Savitsky – Golay smoothing (Savitzky and Golay, 1964) (a form of moving window polynomial) fit was used.
- Split the fitted curve into as many tonnage increments as there are blocks in the model (231 614 blocks in this case). The resulting ascending cut-offs become the new ranked block grades.
- Import these ranked grades, derived from the global change of support histogram, back to the underlying OK block model using the OK rank identifier to locate each new grade of the corresponding rank.

Two test estimates

This implementation of rank and replace method is based around a global change of support calculation via the Gaussian anamorphosis. This utilises the entire domain statistics and requires declustered data for correct implementation. Ideally the domain should also be stationary for this technique to work well. We know that the 100 domain is not stationary and that drill spacing varies widely making declustering necessary for the correct global mean of the anamorphosis.

In these circumstances the RR method it is not expected to work well. Accordingly, two RR models have been estimated, one using the full 100 domain data and another using only the data within the GTM100 sub domain. Although the GTM100 sub domain still contains significant trends, the drill spacing is much more even and declustering, although still used, has a far smaller effect on the shape of the SMU distribution.

Top-cutting

Top-cutting was kept the same, at 25 ppm, as that used for OK estimation in both the resource model and the GTM.

Declustering

Given the widely varying drill spacing declustering is necessary to appropriately weight the data for assessment of global statistics. Separate sets of weights were calculated for the full 100 domain and for within the GTM100 subdomain.

Using declustering weights for variography is preferred by some practitioners and rejected outright by others. In this case, as the change of support calculation needs to maintain consistency between the variogram total sill and the declustered sample variance used in the anamorphosis, variography is completed using declustering weights. The choice of method for calculating and choosing an appropriate set of declustering weights is a difficult one (Olea, 2007) but generally dictated by the software directly at hand.

Variography

Variography from the resource estimation was used for the full 100 domain and new variography completed for the GTM100 sub domain. The new variography utilised both declustering weights and top cut grades to maintain consistency with the original resource and GTM estimates.

Gaussian transform on point data

Gaussian transforms using hermite polynomials were calculated using top cut and declustered data for both the full 100 domain and the GTM 100 sub domain. These are required for the global change of support. A test for bi- Gaussian normality is that the square root of the variogram over the madogram of the Gaussian transformed data should be constant and was found to be the case.

Change of support

Theoretical block distributions at the resource block size of 12.5 m × 12.5 m × 12 m were calculated via the discrete Gaussian method again for both the full 100 domain and the GTM100 sub domain. Top cut and declustered variography was used to maintain consistency throughout.

Individual block grades from theoretical distribution

The tonnage curve (tonnage versus cut off) of the theoretical block distributions were exported. 5000 very finely spaced cut offs were used to maintain sufficient detail in the upper parts of the curve. This point set was then fitted with a moving window polynomial curve. The tonnage axis is then split into the exact number of blocks in the domain and the corresponding cut offs become the ranked block grades (as yet not associated with any location).

Rank and replace

Finally the block model OK grades are then ranked from smallest to largest and the new RR grades are assigned to their locations by matching the curve rank with the kriged rank. The RR results utilising the full 100 domain anamorphosis and global change of support will be referred to as RR RESDEV 100. The RR results

utilising the anamorphosis and global change of support from the GTM100 sub domain will be referred to as RR RESDEV GTM.

RESULTS

Visual assessment

A single level of the GTM100 subdomain is shown in Figure 5. It can be seen that RR RESDEV 100 produces excessive proportions of high-grade compared to all other models. The OK GC estimate can be seen to be picking out more subtle features in the grade distribution due to the increased density of drilling. Higher highs and lower lows are evident in the RR RESDEV GTM estimate.

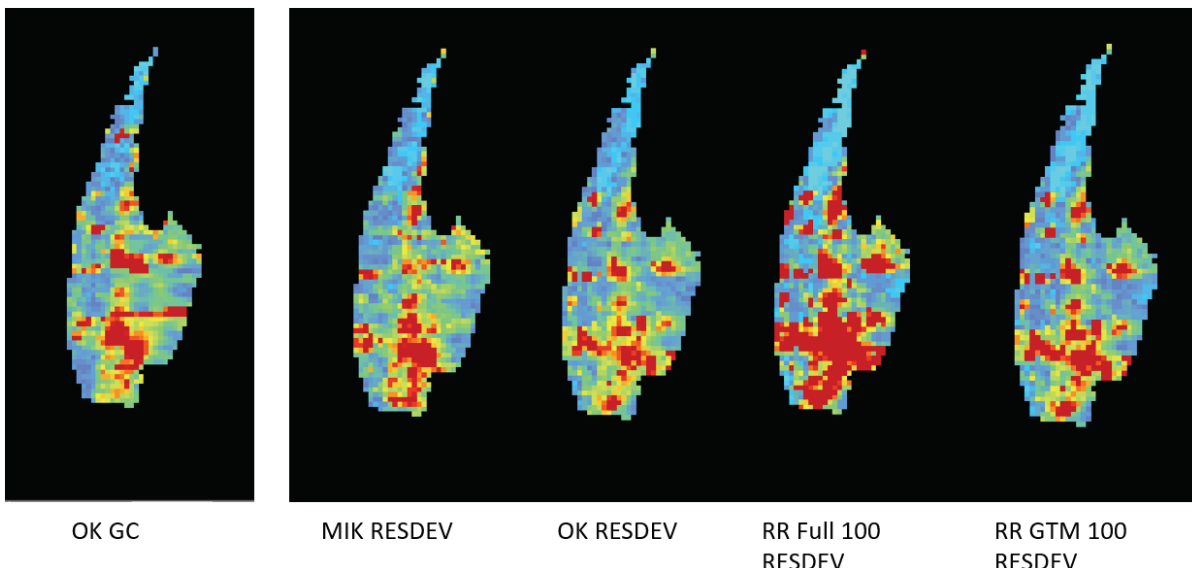


FIG 5 – Au blocks from a single level of the GTM100 sub domain.

Prediction – grade tonnage curves

Prediction is what the models say will happen, for example, tonnages and grades at different cut offs. This can be compared to the prediction of our ground truth model (if we have one). Grade and tonnage curves are inherently global.

Figure 6 shows the grade tonnage and metal curves for the full 100 domain. The RR RESDEV 100 curves are significantly different from the MIK RESDEV and OK RESDEV curves. Although we do not have a reference reality model for the full domain the degree of departure from MIK and OK suggests unacceptable performance of the RR RESDEV 100 method for the full domain.

Figure 7 shows the grade tonnage and metal curves for the GTM100 sub domain. Firstly the very obvious gross overcall of grade at zero cut off for RR RESDEV 100 can be seen. For the grade curves it can be seen that at higher cut offs MIK RESDEV is well below both OK RESDEV and OK GC. This is somewhat contrary to expectations and we are expecting the MIK (mosaic model) estimate to do better overall. We can also see that RR RESDEV 100 grade curve is well above OK GC. Interestingly the OK RESDEV GTM grade curve is closer to the OK GC than the MIK RESDEV at higher cut offs.

With the tonnage curves the RR RESDEV GTM curve starts with the other models, dips lower below the mean of the domain and crossed near the mean to run higher at cut- offs above the mean. This is a typical pattern seen when comparing true estimates to smoothed estimates that lack the highest highs and lowest lows seen in a block distribution with true variability.

Performance

Performance is the interaction with our reference ‘reality’. In other words, performance shows what results when the RESDEV model is used for actual selection at specific cut offs. The true grades from the GTM as selected by the RESDEV model are evaluated. Performance is local in that it is a direct block by block comparison.

Scatter plots and conditional expectation

The three scatterplots shown in Figure 8 show the block scatter, correlations (Rho values) and conditional expectation curves of the various methods against the ground truth OK GC for the GTM100 subdomain. The

Rho value for RR RESDEV GTM, although similar, is the lowest of the three due to the outliers. Note that the RR RESDEV GTM model has a wider scatter than the OK RESEDEV and the MIK RESEDEV estimates and is producing higher high-grade blocks. These scatter plots are sometimes called misclassification plots as they can be marked up to show four quadrants where blocks are either correctly or incorrectly classified at any chosen cut-off.

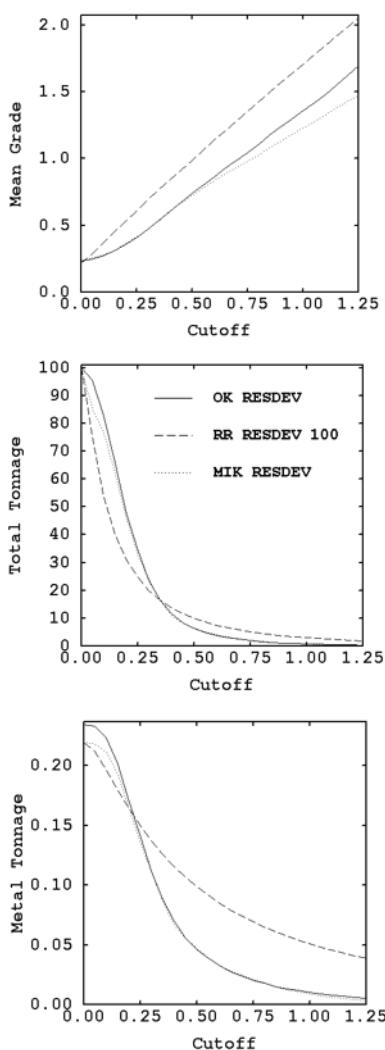


FIG 6 – Prediction – grade tonnage and metal curves for the full 100 domain.

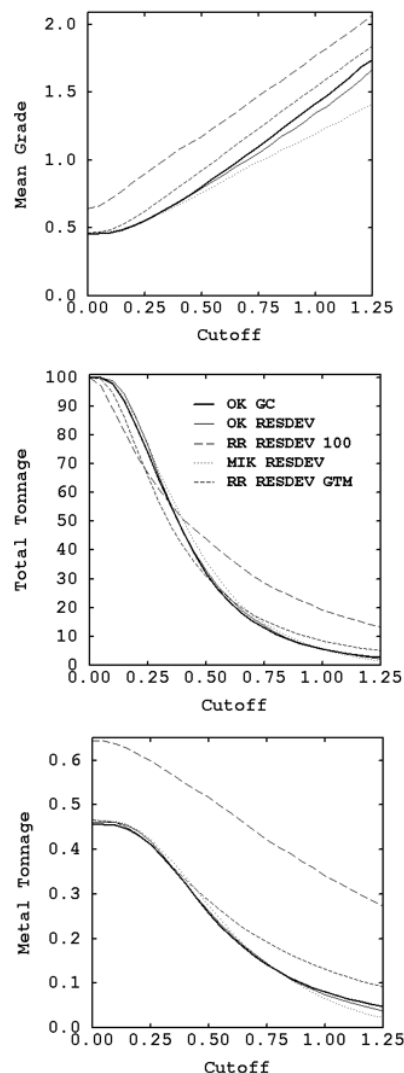


FIG 7 – Prediction – grade, tonnage and metal curves for GTM100 sub domain.

Performance grade tonnage curves

The presentation of performance curves is not often used in geostatistics, partly due to the unavoidable absence of a ground truth model premining. In this case we do have a ground truth model (which we think is closer to reality, it may not be) and we can show how each method performs in terms of actual block selection. This is useful because it gives us an idea of how good the model is for detailed mine planning where a degree of locational precision is required when designing pits and/ or stopes. In practice, additional drilling and sampling is usually completed before a deposit is mined and actual selection takes place using the grade control model not the resource model.

Figure 9 shows the performance curves. None of the methods correctly select high the grades found in the GTM at cut-offs above the mean. As previously, RR RESDEV 100 is completely inappropriate. It can be seen that on a metal basis MIK RESEDEV is closest to the OK GC and RR RESDEV GTM is further away at cut-offs below the mean.

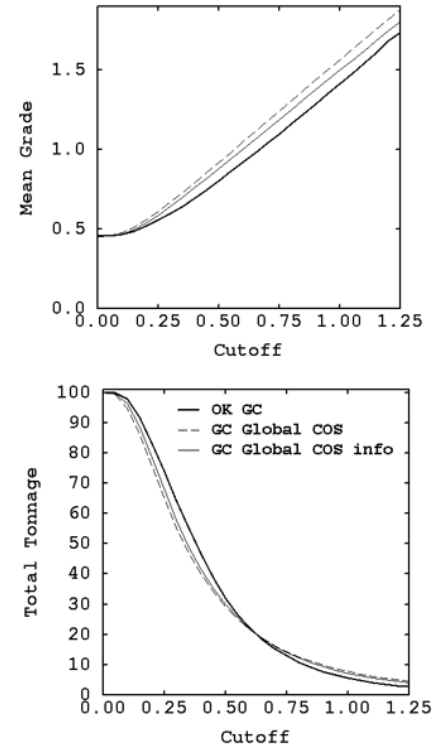
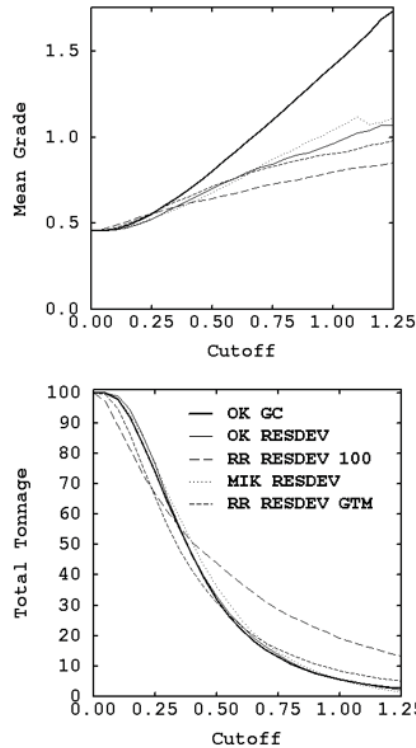
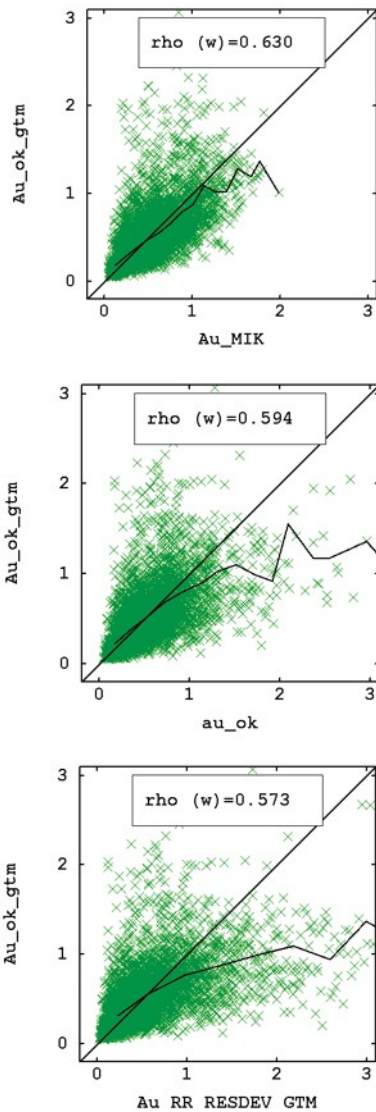


FIG 8 – Performance – scatterplots and conditional expectation curves of GTM grades against MIK RESDEV, OK RESEV and RR RESDEV GTM within the GTM100 sub domain.

FIG 9 – Performance – grade tonnage and metal curves for the GTM100 sub domain.

FIG 10 – Performance – grade tonnage and metal curves for the GTM100 sub domain.

What is reality?

The grade control data within the GTM100 sub domain is fairly closely spaced and the OK GC estimation gives good average kriging regression slopes in excess of 0.9. However, the global change of support assuming perfect knowledge from the GC data (Figure 10) indicates that the OK GC estimate may still be smoothing the block distribution somewhat. The difference in metal around the approximate economic cut off of 0.25 ppm Au is negligible at around 2 per cent but there is a compensating difference for tonnage and grade in the order of 15 per cent. Introducing the information effect based on 7 m x 8 m spaced grade control holes brings the global change of support grade and tonnage curves closer to the GC OK estimate (Figure 10) but they are still not matching. The question is then, when using the GC data, which estimation parameters and/or method creates the closest approximation to reality to use as our reference ground truth model? Even with much more information from the grade control we have the same problem as the one we set out to solve only at a smaller scale.

This casts some doubt on the reliability of the GTM as a true reference reality as the block estimate may still be missing the highest highs and lowest lows compared to reality.

CONCLUSIONS

Used on the whole domain and evaluated on a small section RR is completely inappropriate in this setting (severe non-stationarity and highly varying drill spacing). This should not be surprising given the stationarity requirements for global change of support are stricter than those of local estimators such as OK and E-type MIK and the issues surrounding choice of declustering weights.

Used within the constraints of a small sub section RR exhibits the typical features of a true variability discrete Gaussian model in that it is reasonably close to OK and E-type MIK but predicts more grade and less tonnage at cut-offs below the mean. The RR model is producing higher block variability compared to the GTM. The RR method does not predict or perform as well as OK or E-type MIK in this setting.

It is not clear if these differences are due to deficiencies in the RR method related to non-stationarity and clustering or if the GTM is still significantly smoother than reality. It is possible that both of these aspects are contributing to the observed differences.

The E-type MIK estimate works very well in this setting compared to the GTM but is still smoothing to a certain degree.

The basic principal of Rank and Replace is not reliant on a discrete Gaussian change of support framework although that is what has been applied here. The idea is simply to take any model estimation method that targets true SMU block variability and map the SMU distribution back onto any model/estimation method that targets local SMU block accuracy. Bearing this in mind a change of support model that works with both diffusive and mosaic types of distributions such as that proposed by Machuca-Mory, Babak and Deutsch (2008) may be worth investigating further.

It would be interesting to extend this study and test the methods with sparser resource drill spacing (but within the GTM100 sub domain) as previous studies (Kentwell, 2007) with RR have shown distinct improvements against both OK and non-linear methods at SMU block scale where the underlying OK estimates are poor (regression slopes <0.8).

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REFERENCES

- Abzalov, M, 2006. Localised uniform conditioning (LUC): a new approach for direct modelling of small blocks, *Mathematical Geology*, 38(4):93–411.
- Isaaks, E, 2005. The Kriging oxymoron: a conditionally unbiased and accurate predictor (2nd Edition), in *Proceedings Geostatistics Banff 2004* (eds: O Leuangthong and C V Deutsch), pp 363–374 (Springer).
- Journel, A G, Kyriakidis, P C and Mao, S, 2000. Correcting the smoothing effect of estimators, *Mathematical Geology*, 32(7):787–813.
- Kentwell, D, 2017. Approaching simultaneous local and global accuracy, in *Proceedings Geostatistics Valencia 2016* (eds: J J Gomez- Hernandez, J Rodrigo-Illarri, M E Rodrigo-Clavero, E Cassiraga and J A Vargas-Guzmán) pp 245–257 (Springer).
- Krige, D G, 1951. A statistical approach to some basic mine valuation problems on the Witwatersrand, *Journal of the Chemical Metallurgical and Mining Society of South Africa*, 52(6):119–139.
- Krige, D G, 1994. An analysis of some essential basic tenets of geostatistics not always practiced in ore valuations, in *Proceedings First Regional APCOM, Slovenia*, pp 15–28.
- Krige, D G, 1996. A basic perspective on the roles of classical statistics, data search routines, conditional biases and information and smoothing effects in ore block valuations, in *Proceedings Conference on Mining Geostatistics, Kruger National Park, Sept, 1994 (UNISA)*.
- Machuca-Mory, D F, Babak, O and Deutsch, C V, 2008. Flexible change of support model suitable for a wide range of mineralisation styles, *Mining Engineering*, 60(2):63.
- Olea, R A, 2007. Declustering of clustered preferential sampling for histogram and semivariogram inference, *Mathematical Geology*, 39:453–467.
- Richmond, A, Gaze, A and Horton, J, 2009. Desmoothing block models for underground mine design, in *Proceedings Seventh International Mining Geology Conference*, pp 265–268 (The Australian Institute of Mining and Metallurgy).