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Implementation of Localised Uniform Conditioning for Recoverable Resource Estimation at the Kipoi Copper Project, DRC

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ABSTRACT

The Kipoi Central (KPC) copper project is located in the Katanga Province in the Democratic Republic of the Congo and is presented here as an example of an operating mine where the Mineral Resource was initially estimated by Uniform Conditioning (UC) and subsequently updated to Localised Uniform Conditioning (LUC). This paper discusses the implementation of an estimate run using LUC and compares the results based on resource definition drilling to those obtained by close spaced grade control drilling and actual mill production.

UC is a non-linear geostatistical technique designed for recoverable resource estimation, typically using wide spaced exploration and resource definition drilling. The primary output of UC is the grade, tonnage and metal above a series of user-defined cut-off grades for a particular Selective Mining Unit (SMU) block size. The UC approach is considered to provide a more accurate representation of the recoverable grade and tonnage at SMU support for non-zero grade cut-offs than would typically be achieved by a traditional linear estimator such as Ordinary Kriging. LUC is a relatively new approach involving the post-processing of a UC estimate and is used to spatially present the grade distribution predicted by UC at the SMU scale.

This study demonstrates that the calculation of a more accurate and realistic grade-tonnage relationship for small SMU sized blocks is possible at the exploration stage using LUC, provided that the necessary theoretical and practical conditions for implementation of this technique exist.

INTRODUCTION

The Kipoi Central (KPC) copper project, operated by Tiger Resources Limited, is located 85km north-northwest of Lubumbashi, the provincial capital of Katanga Province in the Democratic Republic of the Congo (DRC) (Figure 1). Stage 1 open pit mining operations commenced in November 2010, focussing on the mining of high-grade oxide ore. The oxide ore is processed in a heavy mineral separation plant to produce a saleable concentrate. This study aims to demonstrate the benefit in applying a non-linear estimation method such as LUC at the resource definition drilling stage to a deposit that satisfies the requisite conditions.

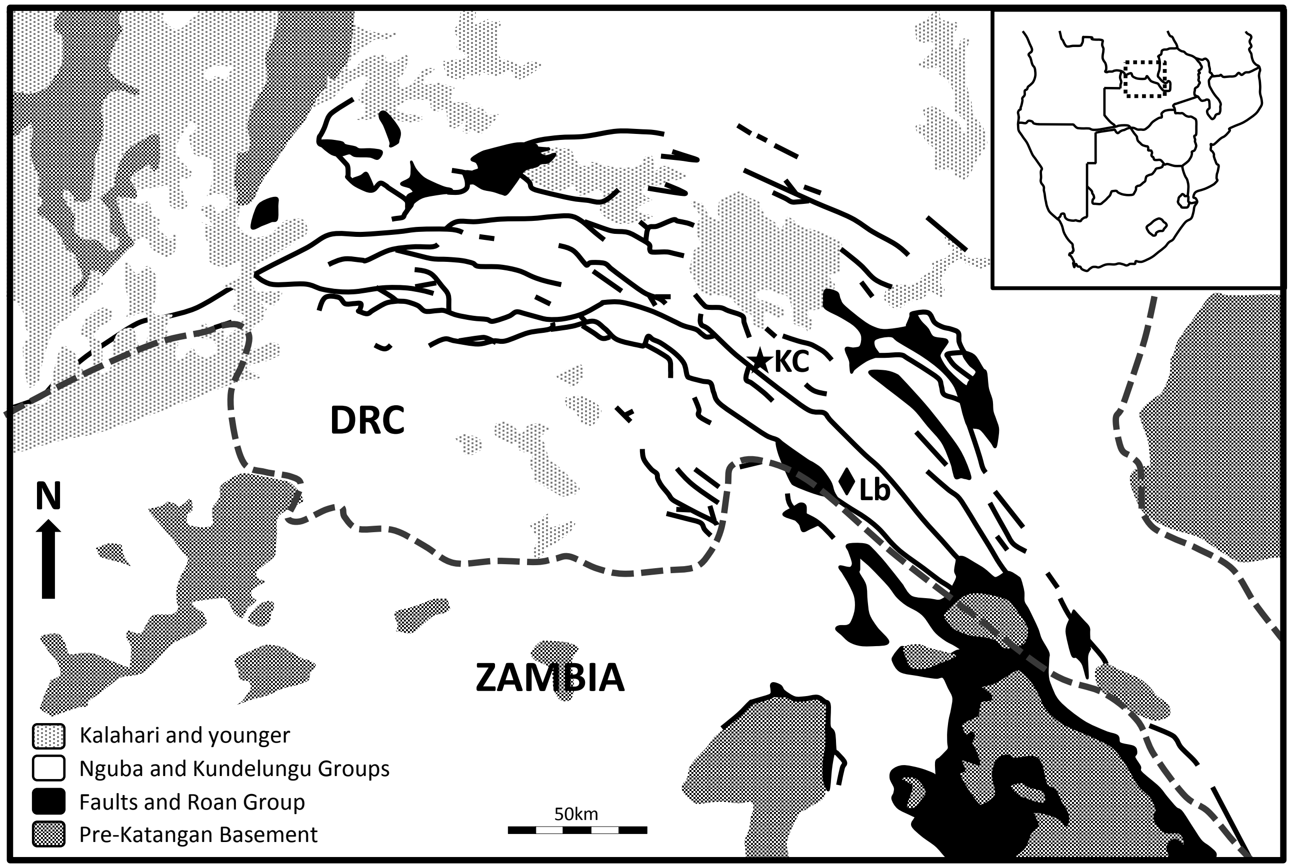

FIG 1 – A map showing the location of the Kipoi Central deposit (KC) relative to the capital of Katanga Province, Lubumbashi (Lb). The distribution of rocks of the Katanga Supergroup, inclusive of the Roan, Nguba and Kundelungu Groups, are shown along with older basement and younger cover (after François, 1974).

GEOLOGY

The KPC orebody is hosted within Upper Roan Group sediments, forming part of the arcuate Central African Copper Belt, also known as the Lufilian Arc, which extends approximately 700km from northeastern Zambia, through the DRC, to the Angolan border area (Figure 1). Field observations from the non-oxidised zone show that copper mineralisation, manifest primarily as chalcopyrite, occurs in sedimentary pore space (stratiform), as cross-cutting and bedding-parallel veins and in breccias of tectonic origin (Dorling et al, 2009). The host rock comprises mostly dolomitic siltstones, pyroclastics and dolomites.

The primary mineralisation has subsequently been remobilised by near-surface processes in the higher-grade oxide zone. Malachite is the principal copper-bearing mineral in the oxidised zone, with minor amounts of azurite, pseudomalachite, chalcocite, bornite and native copper also occurring. Oxide mineralisation occurs as in-situ replacement of stratabound sulphides, as coatings on bedding, cleavage and joint surfaces and as minor cavity infill and consequently the oxide mineralisation is dispersed over a much larger rock volume than is the case for primary mineralisation in fresh rock.

MINERALISATION DOMAINS

The KPC deposit is divided into three domains for the estimation of copper using only the exploration drill data. The domain boundaries are based on a combination of grade tenor and the association of higher- and lower-grade mineralisation with specific lithologies:

1. Domain 200 – higher-grade zone strongly associated with siltstones; shoot plunges gently (~25°) to the south-southwest; incorporates primarily oxide ore with subordinate primary sulphides at depth; main target of stage 1 mining.
2. Domain 300 – lower-grade zone associated with dolomites and pyroclastics; incorporates both oxide and primary ore; eastern portion affected by stage 1 mining.
3. Domain 400 – lower-grade zone hosted mainly by pyroclastics; spatially separated from domains 200 and 300; not in stage 1 mine plan.

A gradational boundary exists between domains 200 and 300, and this has been accounted for by a 100m zone of overlap during the selection of estimation input data to avoid any large step changes in the grade estimates. Domain 400 is a separate, spatially distinct zone of low-grade mineralisation situated above the western edge of domain 300 and is defined by a hard boundary.

A copper model based only on grade control drill data has been estimated within a single grade control domain which overlaps largely with domain 200, but impinges on the eastern edge of domain 300. It was not considered necessary to sub-domain this grade control volume. Figure 2 shows the mineralisation domains as well as the composite data used for estimation and the stage 1 pit outline as at the end of December 2013.

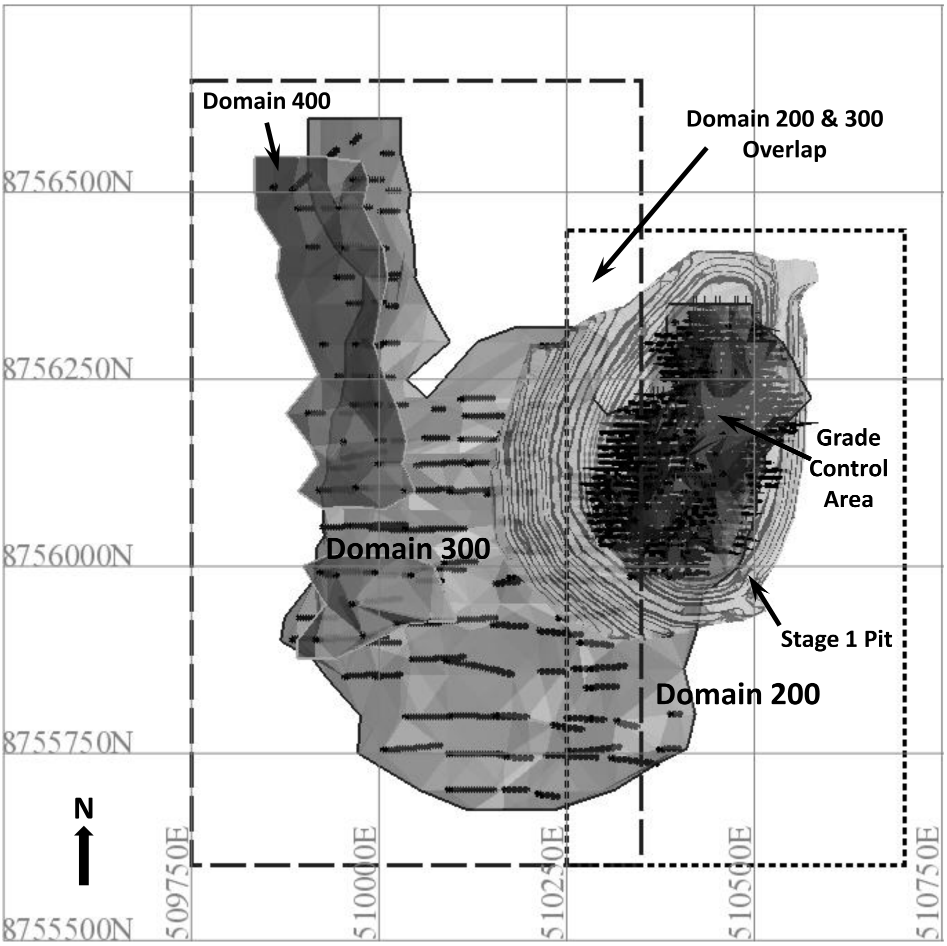

FIG 2 – The mineralisation domains for copper estimation at Kipoi Central.

The boundary between oxide and sulphide mineralisation is typically transitional and the study space is dominated by oxidised material becoming transitional at the base of the stage 1 pit. In addition, a comparison of the oxide and sulphide sample data shows they are statistically similar populations and therefore no segregation of composite data by weathering type is considered necessary.

DATA AND BLOCK MODELS

The exploration dataset for recoverable resource estimation consists predominantly of core samples from diamond drilling (180 holes) along with reverse circulation drill chip samples (25 holes). Drill spacing is dominantly 25 mE x 25 mN in domain 200, stepping out to 50 mE x 50 mN in domains 300 and 400. The majority of holes are inclined at 60° towards the east. Downhole copper assays are composited to 3 m downhole and are coded by mineralisation domain, with domain 200 composites overlapping domain 300 composites to 100 m east of their common boundary. Appropriate cell declustering weights are applied to the data in order to obtain unbiased histograms and variograms.

The grade control drill dataset is composed of samples taken from blast holes (1 398 holes) and reverse circulation holes (2 581 holes) spaced at 5 mE x 10 mN and principally inclined at 60° towards the east. The reverse circulation holes account for the bulk of the drill samples due to their greater depth. The assay data are composited to 3 m downhole for use in the grade control model estimation.

The panel dimensions for estimation are 25 mE x 25 mN x 5 mRL whilst the Selective Mining Unit (SMU) size is 5 mE x 5 mN x 2.5 mRL.

EXPLORATORY DATA ANALYSIS

The relatively high-grade tenor of domain 200 and the largely overlapping grade control domain are clearly evident in the composite basic statistics (Table 1). The copper grades are moderately to highly variable throughout.

TABLE 1

Basic statistics, per estimation domain, for 3 m copper grade composites (units = wt% Cu).

Domain	Drill Campaign	Count	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation
200	Exploration	3 184	0.003	36.30	3.15	4.25	1.35
300	Exploration	3 342	0.003	33.50	0.88	1.49	1.70
400	Exploration	222	0.05	2.03	0.44	0.34	0.79
Grade Control	Grade Control	26 361	0.003	44.13	2.91	4.03	1.39

There are two important preconditions which should be satisfied for the valid application of UC for recoverable resource estimation:

1. Bi-Gaussianity: Pairs of the Gaussian-transformed grade variable (in this case copper grade), separated by a distance *h*, when plotted against one another in an *h*-scatterplot, should define a cloud-shaped ellipse (Figure 3). This is indicative of a spatial bivariate normal distribution.

2. Diffusion: Diffusive conditions exist when we move from a point of low value to a point of high value whilst encountering intermediate values between them (ie major step changes in grade value are not evident at the scale of sampling). A geostatistical test for diffusion involves defining grade indicator variables at a range of cut-offs and plotting the ratio of the cross-variogram of each pair of indicators to the variogram of the lower-grade indicator. An increasing or decreasing function, as opposed to a constant value, is indicative of diffusion between the two grade domains represented by the pair of indicators (Figure 4).

The mineralisation domains at KPC are observed to conform to the two conditions discussed above. Strict Second Order Stationarity Hypothesis is not required for a UC implementation; it is sufficient to satisfy the weaker Intrinsic Hypothesis.

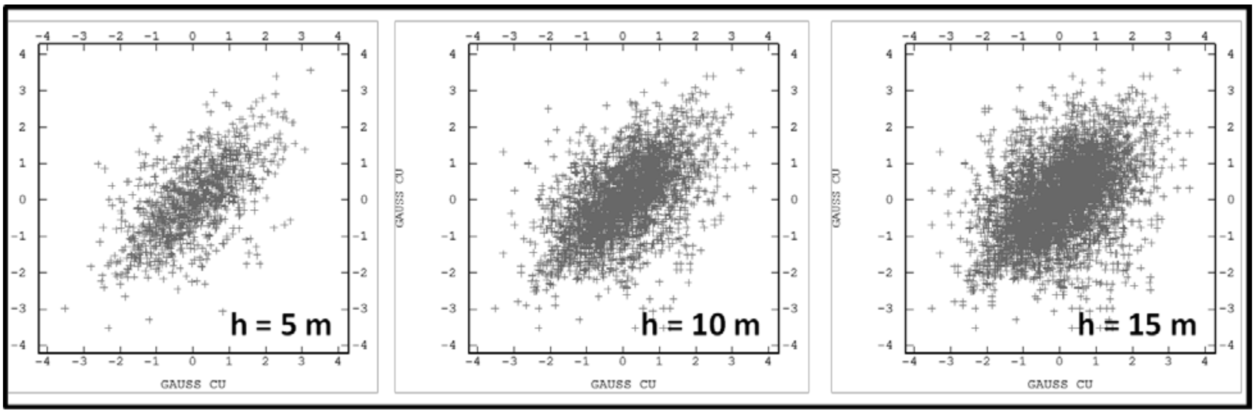

FIG 3 – A series of *h*-scatterplots demonstrating the bigaussian relationship for 3 m composite copper grade in domain 300.

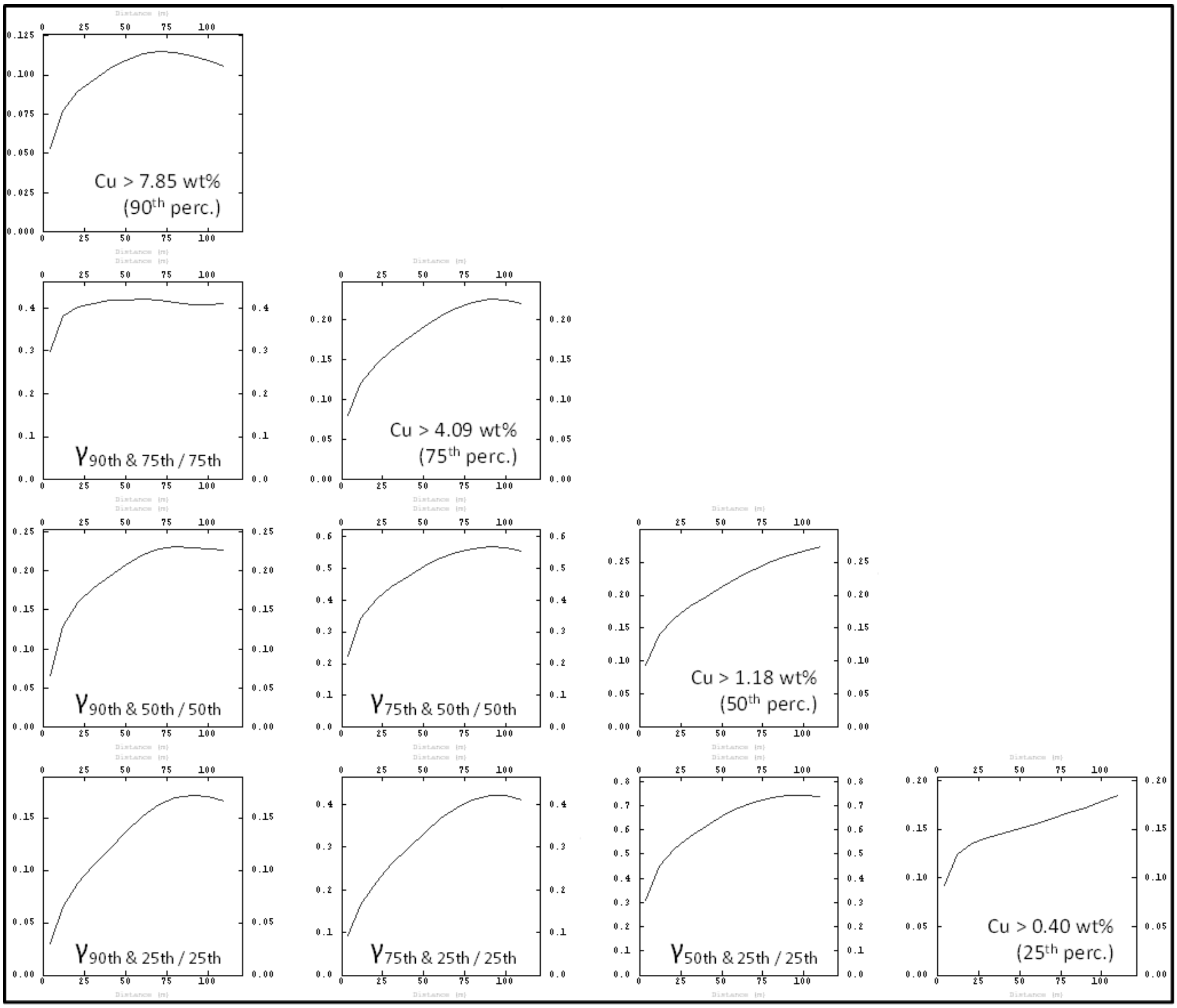

FIG 4 – The diffusion test matrix for copper grade based on grade control 3 m composites. The upper right diagonal shows the indicator variograms for the 25th, 50th, 75th and 90th percentile of the copper grade distribution. To the left of this diagonal are the quotients of the cross variograms to variograms, which describe the state of diffusion at the boundaries between the grade domains.

IMPLEMENTATION OF LOCALISED UNIFORM CONDITIONING

UC and LUC were implemented using the method described by Rivoirard (1994) and Abzalov (2006), respectively. The Isatis software implementation of the relevant algorithms was utilised. The workflow is summarised below:

1. Ordinary Kriging (OK) of copper grade into 25 mE x 25 mN x 5 mRL panels using exploration data only. The theoretical variance of the estimates (ie Var Z*) is stored, along with the panel grade estimate, for later use in UC.

2. Calculate the SMU change of support coefficients using Hermite Polynomial functions in conjunction with the composites sample support grade variograms. An information effect correction is implemented, in this case based on a 10 mN x 5 mE x 2.5 mRL vertical grade control drill pattern.

3. The panel change of support coefficients are calculated automatically at run time based on the Var Z* values stored as part of step 1. A number of iso-frequency classes for Var Z* are defined. Within each class, the mean value of Var Z* is calculated and used to define change of support parameters.

4. Run the UC algorithm, producing outputs for tonnage, grade and metal above 58 selected grade cut-offs.

5. OK of copper grade into the 5 mE x 5 mN x 2.5 mRL SMU blocks, in order to provide a basis for the ranking of grade in SMU's within each panel.

6. Run LUC post-processing to map the results of UC per panel onto the SMU's falling within each panel.

Variogram models are produced by transforming the sample data to Gaussian space and then back-transforming the resulting model to real space. The samples are appropriately declustered. The Gaussian variograms are displayed in Figure 5 while the real space variogram model parameters are summarised in Table 2. The variogram model based on exploration data from domain 300 is applied to both domains 300 and 400 due to the lack of robust experimental spatial structure in domain 400 (too few data points). The UC parameters applied during estimation are presented in Table 3.

TABLE 2

Variogram model parameters used to estimate copper grade at Kipoi Central.

Variable (Domain)	**Nugget**	**Spherical 1**				**Spherical 2**				**Isatis Rotation (Geol Plane)**		
		sill	**major (m)**	**semi (m)**	**minor (m)**	**sill**	**major (m)**	**semi (m)**	**minor (m)**	**Az**	**Ay**	**Ax**
Cu (200)	2.44	5.30	23	20	15	2.60	192	88	53	25	90	-25
Cu (300)	0.4	0.86	23	23	14	0.345	92	92	53	20	0	0
Cu (400)	0.03	0.0645	23	23	14	0.0259	92	92	53	20	0	0

Cu (GC)	3.22	5.90	25	20	15	6.92	230	82	61	25	90	-25

TABLE 3

The UC parameters for domains 200, 300, and 400, as applied to achieve a recoverable estimate for copper based on exploration data.

Parameter	**Domain 200**	**Domain 300**	**Domain 400**
Sample Variance (Declustered)	10.35	1.61	0.12
Variogram Sill	10.34	1.61	0.12
γ(v,v)	3.71	0.56	0.042
Real Block Variance	6.64	1.05	0.078
Real Block CoS Coefficient (r)	0.86	0.87	0.84
Kriged Block Variance	5.83	0.89	0.064
Kriged Block CoS Coefficient (s)	0.82	0.82	0.78
Kriged-Real Block Covariance	5.91	0.91	0.066

GRADE CONTROL MODEL

A copper grade model for the grade control domain was produced by OK using the grade control data. The majority of the grade control volume overlaps domain 200, and therefore only a single variogram model is required (Figure 5 and Table 2).

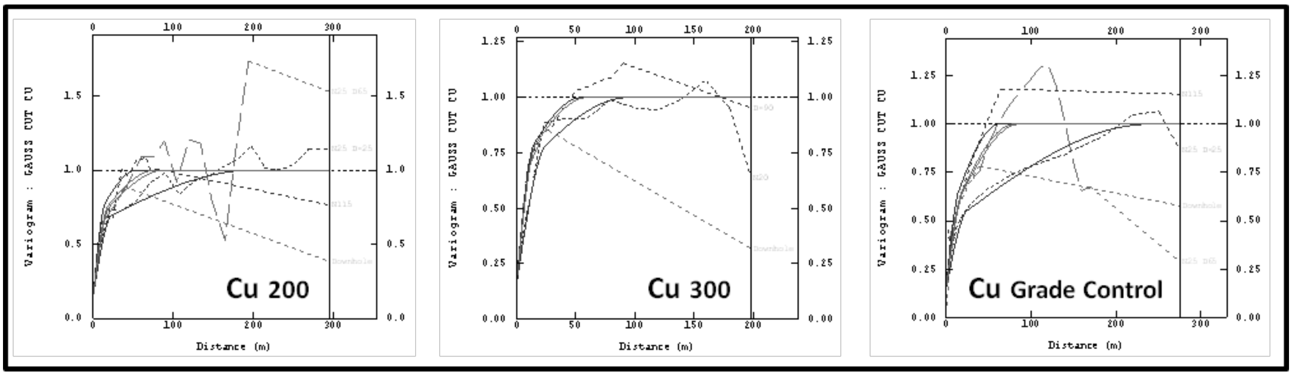

FIG 5 – The Gaussian variogram models upon which the copper grade estimates at Kipoi Central are based. These variograms were back transformed to real space for use in the estimation routines.

COMPARISON

Comparative results are reported within the confines of the stage 1 pit between January 2011 and December 2013. The economic copper grade cut-off used to delineate mill feed was 3.25 wt% Cu to the end of 2012 and thereafter reduced to 3.00 wt% Cu. The time-series results within the pit, including actual production, are reported at these grade cut-offs.

Grade-Tonnage Curves

The grade-tonnage curves for the LUC, panel OK and grade control models (Figure 6) show that the LUC tonnage tracks the grade control model closely up to a cut-off of approximately 2 wt% Cu. Above this, the LUC tonnage departs from the grade control tonnage and approaches the panel OK, with no significant difference being noted between LUC and OK by around the 3.50 wt% Cu cut-off. The grade control model, due to the very dense sampling, is considered to be the benchmark in this comparison. In terms of grade above cut-off, the LUC clearly outperforms the panel OK across the full range of copper grade cut-offs. The LUC metal prediction is similarly significantly closer to the grade control model across the full range of cut-offs (Figure 7).

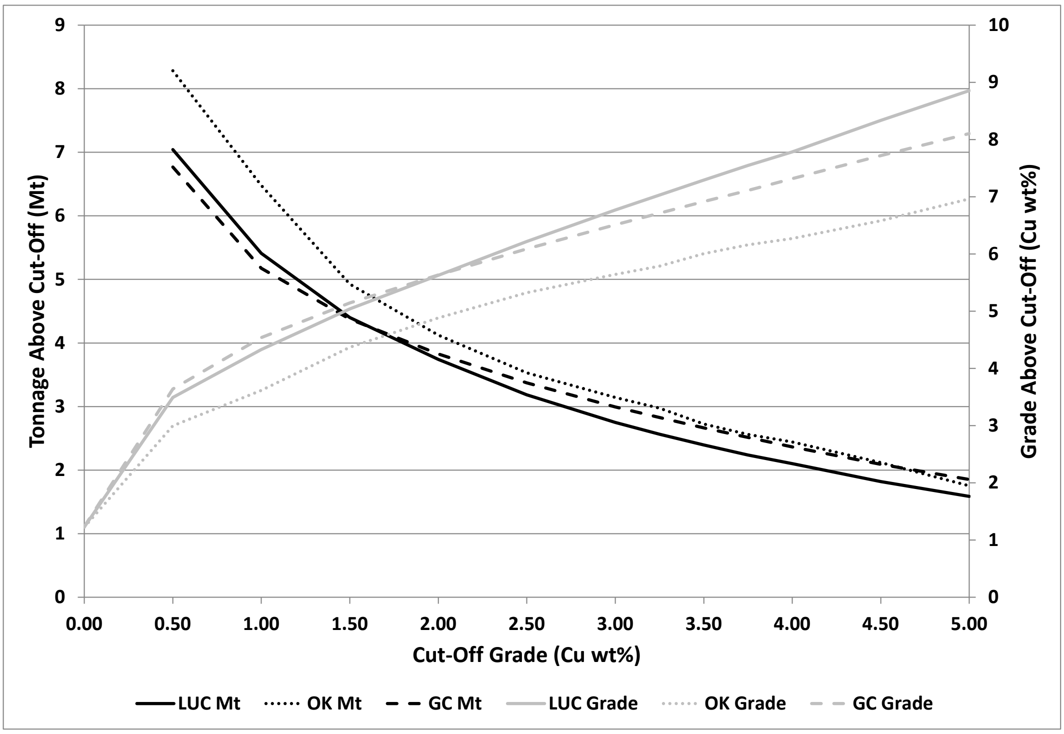

FIG 6 – Grade-tonnage curves for the LUC, panel OK and grade control models, reported within the stage 1 pit to end-December 2013.

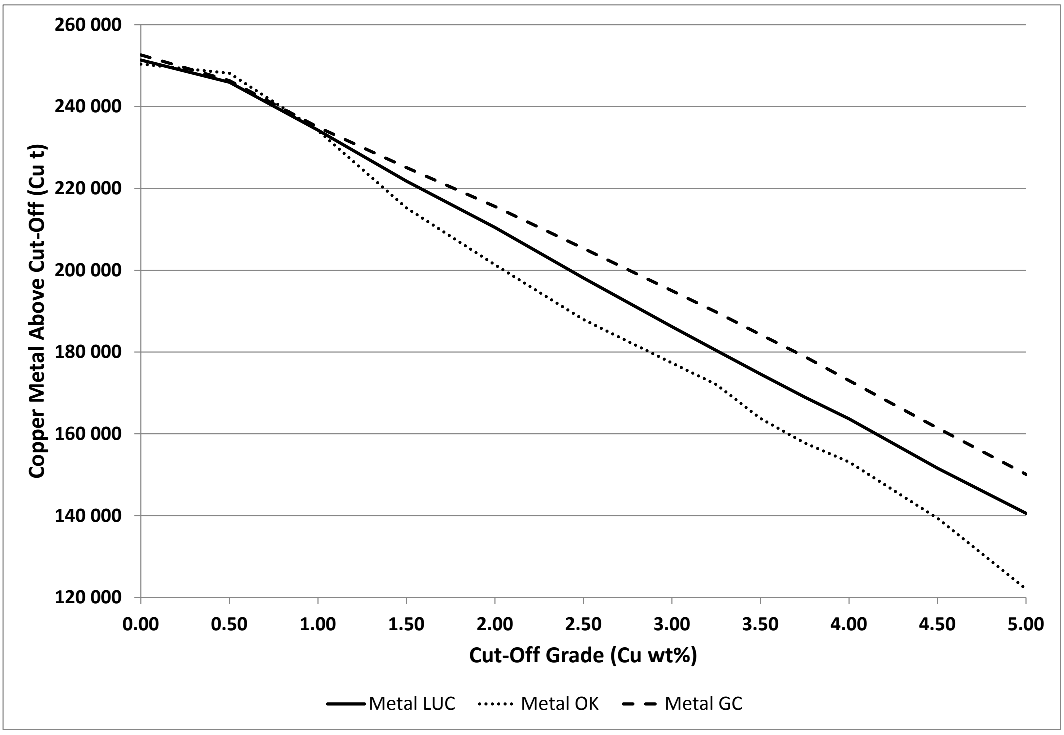

FIG 7 – Metal curves for the LUC, panel OK and grade control models, reported within the stage 1 pit to end-December 2013.

Quarterly Reports

When reported by quarterly production period, the LUC tonnage prediction tracks the grade control model more closely than the panel OK for the first two years, following which the situation is reversed (Figure 8). However, the LUC significantly outperforms the panel OK in terms of predicted grade across all time periods (Figure 9). It is noteworthy that many of the LUC and panel OK blocks corresponding to the 2013 period are situated either at the lateral or basal margins of the more dense 25 mE x 25 mN spaced exploration drill data, and are therefore less reliable than the block estimates for the first two years of mining. In this regard, it is also important to recognise that the variogram models generally transition from the relatively strong short range structures to the weaker long range ones beyond a distance of approximately 20 m.

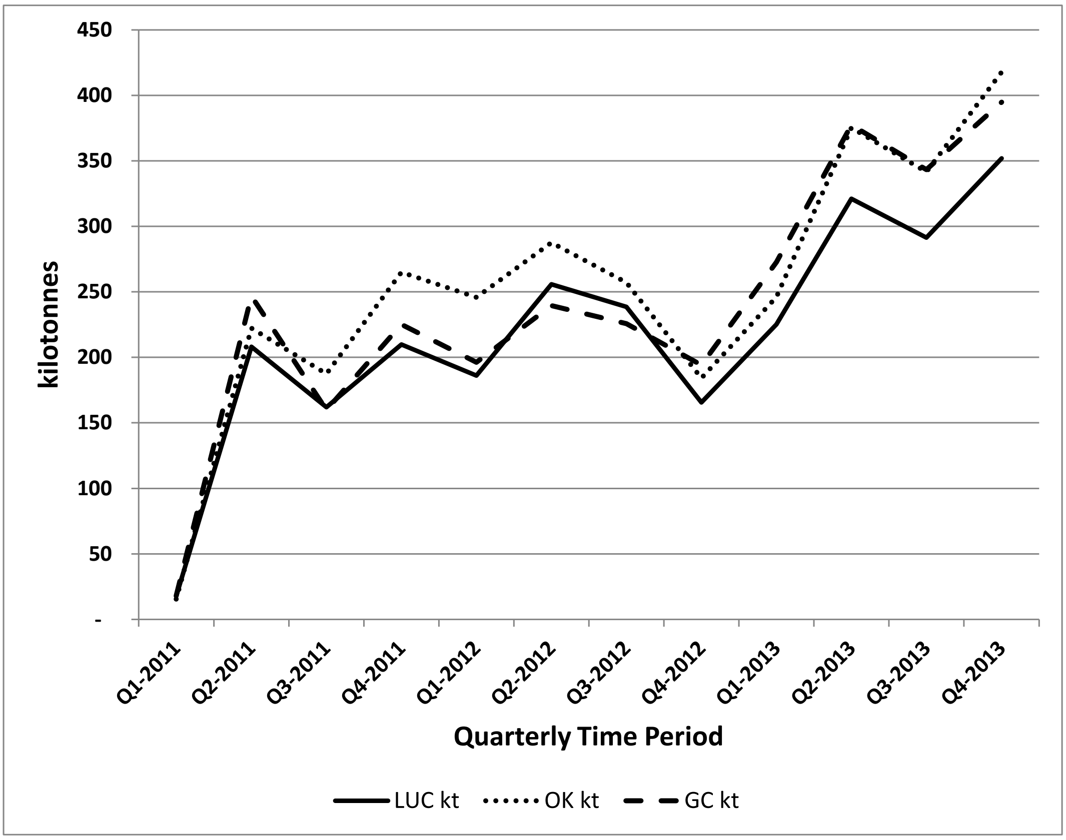

FIG 8 – Comparison of LUC, panel OK and grade control model tonnages above the economic cut-off within the stage 1 pit, reported by quarterly production period.

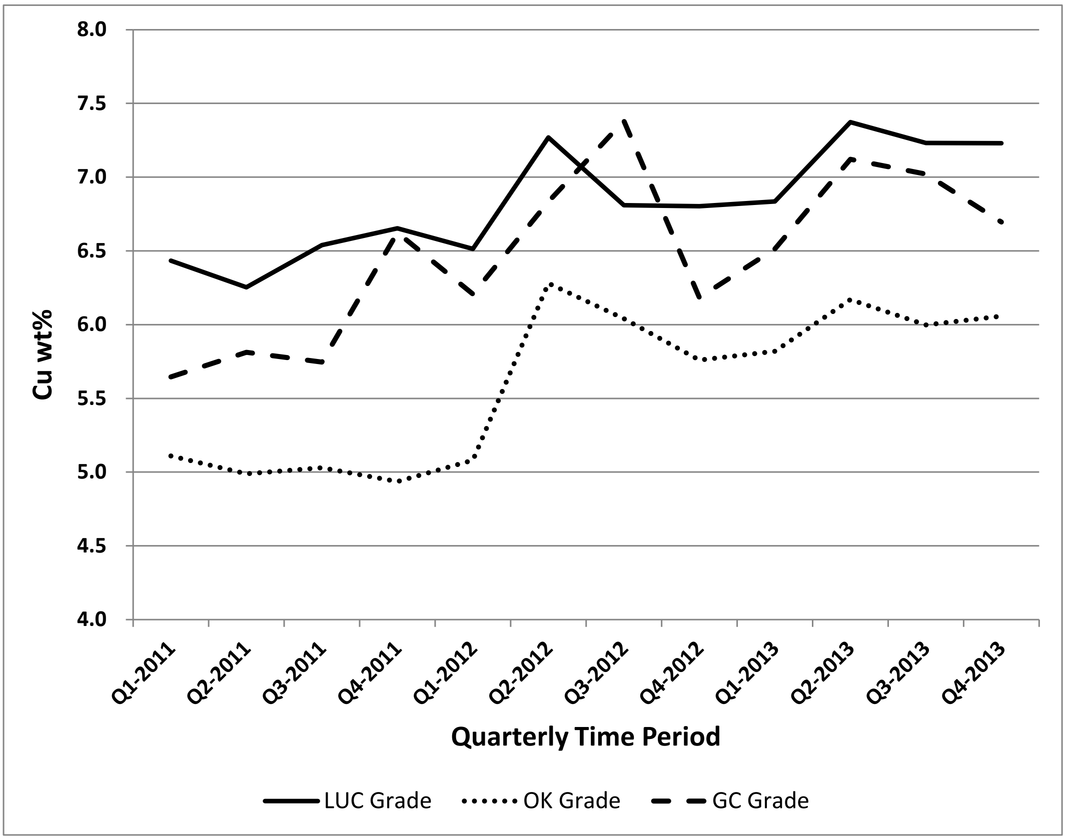

FIG 9 – Comparison of LUC, panel OK and grade control model grades above the economic cut-off within the stage 1 pit, reported by quarterly production period.

Global Comparison to Actuals

The LUC, panel OK and grade control model predictions are compared to actual mill and stockpile figures in Table 4. As expected, the grade control model delivers the most accurate results, especially in terms of recovered grade and metal. The LUC model is significantly better matched to actual production in terms of grade and metal recovery than is the panel OK model. The actual tonnage is slightly higher than both the LUC and grade control models, and this could be due to planned dilution by incorporation of lower-grade material in mining dig blocks. For the same reason, the actual recovered grade is lower than either the LUC or grade control models.

TABLE 4

Comparison of LUC, panel OK and grade control models predictions to actual production figures above the economic cut-off, within the stage 1 pit, to end-December 2013.

Source	**Mt**	**Cu (wt%)**	**Cu (kt)**
panel OK	3.05	5.7	174
LUC	2.63	6.9	182
grade control	2.89	6.6	191
Milled + Stockpile	2.97	6.5	193

CONCLUSIONS

This study demonstrates that a non-linear geostatistical method such as LUC, designed to estimate recoverable resources at the SMU scale, is able to generate quantifiably more accurate predictions than a linear method, such as OK, at the exploration stage. As long as the conditions for the valid application of LUC are met, use of this method, or another applicable non-linear approach, should be preferred to the alternative of settling for a linear estimate. However, where the data spacing is wide relative to the practical range of the variogram model, the effectiveness and reliability of non-linear methods such as LUC will be reduced.

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