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Stochastic rock type modeling in a porphyry copper deposit and its application to copper grade evaluation

Hassan Talebi [a,*], Omid Asghari [b], Xavier Emery [c,d]

[a] Department of Mining Engineering, University of Tehran, Iran
[b] Simulation and Data Processing Laboratory, School of Mining Engineering, University College of Engineering, University of Tehran, Tehran, Iran
[c] Department of Mining Engineering, University of Chile, Chile
[d] Advanced Mining Technology Center, University of Chile, Chile

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ABSTRACT

An accurate definition of geological domains that differentiate the types of mineralogy, alteration and lithology is a critical step in mineral resources and ore reserves evaluation. Deterministic models define just one interpretation of the layout of these domains, based on drill hole data and mining geologist point of view, but do not take into account the uncertainty in areas with fewer data and do not offer any measure of the uncertainty in the domain boundaries. Instead, stochastic models based on geostatistical simulation allow assessing the uncertainty in the spatial layout of the domains. This study addresses the application of plurigaussian simulation in order to simulate the layout of porphyry, skarn and non-mineralized dykes in Sungun porphyry copper deposit (Iran) and to map their probabilities of occurrence over the region of interest. These probabilities are then used for weighting the copper grade prediction associated with each domain so as to obtain the final grade model. Results show the continuity of the grades proper to each domain and across domain boundaries, and compare favorably with respect to the approach based on deterministic geological modeling.

1. Introduction

An accurate resource evaluation in heterogeneous ore deposits requires defining domains that differentiate the types of mineralogy, alteration and lithology. The most prevalent approach is to deterministically divide the ore body into such domains and to predict the grades of elements of interest within each domain separately by means of geostatistical tools (Dowd, 1986; Duke and Hanna, 2001; Rossi and Deutsch, 2014). A shortage of this approach is that the mining geologists have to delineate the exact shape of each domain in the ore deposit, which in practice is illusory. Accordingly, this methodology fails at measuring the uncertainty in the domain layout and at reproducing the true spatial variability of the grades. Geostatistical simulation improves the domain definition and quantifies the uncertainty in the position of their boundaries, by constructing multiple numerical models (called realizations) that reproduce spatial variability and, therefore, provide realistic outcomes of the geological domain layout. To date, many simulation models have been proposed, such as sequential indicator (Journel and Alabert, 1990; Journel and Gómez-Hernández, 1993; Deutsch, 2006), multiple-point (Strebelle, 2002; Mariethoz and Caers, 2015), truncated Gaussian (Matheron et al., 1987) and plurigaussian (Armstrong et al., 2011) simulation. The pros and cons of these models have been discussed in the literature (Chilès and Delfiner, 2012) and are out of the scope of this work. The applicability of geostatistical simulation, especially plurigaussian, to model the layout of geological domains such as barren dykes has been shown in previous studies (Carrasco et al., 2007; Riquelme et al., 2008; Madani and Emery, 2014; Yunsel and Ersoy, 2013; Talebi et al., 2013, 2014; Rezaee et al., 2014).

The aim of this study is to implement, through a case study, a methodology that improves the prediction of mineral grades, via a stochastic modeling of the geological domains that control the grade distribution. Following Emery and González (2007a, b), the probabilities of occurrence of each domain will be used to obtain the final grade model and the results will be compared to the conventional geostatistical methodology.

2. Case study

Sungun porphyry copper deposit is located in northwestern Iran and is associated with diorite–granodiorite to quartz monzonite of Miocene age, which intruded Eocene volcano-sedimentary and Cretaceous carbonate rocks. The emplacement of the Sungun stock occurred in several intrusive pulses with hydrothermal activity (Hezarkhani and Williams-Jones, 1998; Hezarkhani, 2006). The arrangement of mineralization zones does not follow the simple models of porphyry systems.

* Corresponding author.
E-mail addresses: h.talebi@ut.ac.ir (H. Talebi), o.asghari@ut.ac.ir (O. Asghari), xemery@ing.uchile.cl (X. Emery).

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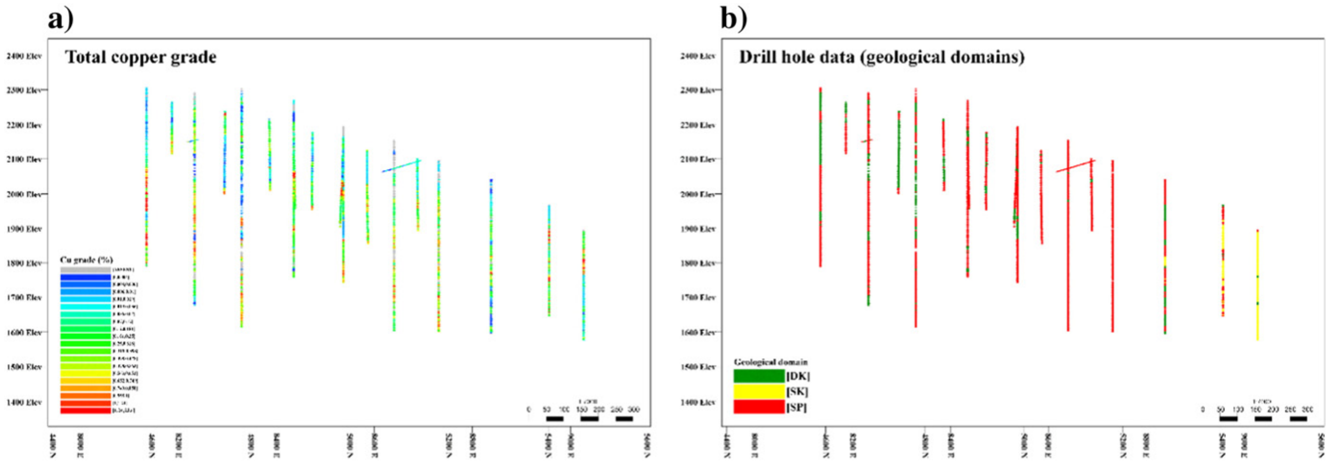

Fig. 1. A cross section of available data showing, a) distribution of copper grade and b) main rock type domains.

Table 1
Statistical parameters of copper grade (in percent), for each rock type domain and overall.

	Number of the data	Mean	Median	Mode	Std. deviation	Variance	Skewness	Kurtosis	Minimum	Maximum
DK	9016	0.08	0.01	0.01	0.22	0.04	6.30	59.39	0	3.58
SK	749	0.57	0.26	0.01	1.28	1.64	10.23	154.46	0	23.50
SP	20664	0.53	0.45	0.01	0.48	0.23	2.60	24.023	0	9.61
Total	30430	0.40	0.25	0.01	0.51	0.25	6.23	177.63	0	23.50

The most important factor in supporting this fact is the diversity, size and density of the late-injected dykes into the main intrusion mass of Sungun porphyry copper deposit (Mehrpartou, 1993). These dykes often do not have any mineralization and their thickness varies from a few centimeters to several tens of meters.

Three main rock types controlling the copper grade distribution are identified in Sungun deposit (Asghari et al., 2009):

- *Sungun porphyry* (*SP*): this is the main intrusion mass of Sungun with porphyry fabric and composition of quartz monzonite.
- *Non-mineralized dykes* (*DK*): late-injected dykes cross-cut Sungun porphyry in several times and places.
- *Skarn* (*SK*): in the eastern and northern margins of the porphyry stock, there is a metasomatic contact alteration and mineralization with the upper Cretaceous limestone and marl.

2.1. Dataset

For this study, we selected a set of vertical and oriented exploration drill holes and focused on a volume of 1000 m along the east–west, 1200 m along the north–south and 1100 m vertically. The drill holes have been logged every 2 m, totaling 34,035 sample points with information on the total copper grade and the rock type. Fig. 1 shows a cross-section of the available data. The statistical parameters of the copper grade, globally and per rock type domain, are presented in Table 1, and their cumulative frequency in Fig. 2. It is seen that the grade distribution strongly differs between one domain and another. Dykes practically do not have economic mineralization and correspond to waste material not to be sent to the processing plant. This led mine geologists to separate the rock type domains prior to the resources evaluation process, as different behaviors are expected in these domains.

The spatial variability of the copper grade also depends on the rock type domain (Fig. 3). Calculating the copper grade variograms in different directions shows that the horizontal direction with the greatest spatial continuity is oriented 150° with respect to the north. The anisotropy of SP and SK is approximately the same, but the copper grade in SK domain exhibit more variation than in other domains. The DK domain has an inclination of about 30° toward south-west.

2.2. Stochastic modeling of rock type domains

Plurigaussian simulation (Lantuéjoul, 2002; Armstrong et al., 2011, and references therein) is a well-known approach that aims at reproducing the layout of geological domains forming a partition of space. The domains are produced based on truncating two or more Gaussian random fields. The model is defined by a truncation rule that provides information about the permissible and forbidden contacts between geological domains, and by the Gaussian field variograms, which describe the spatial variability of the domains.

In Sungun porphyry copper deposit, the rock type domains (SP, DK, SK) are mutually in contact. In such a circumstance, two independent

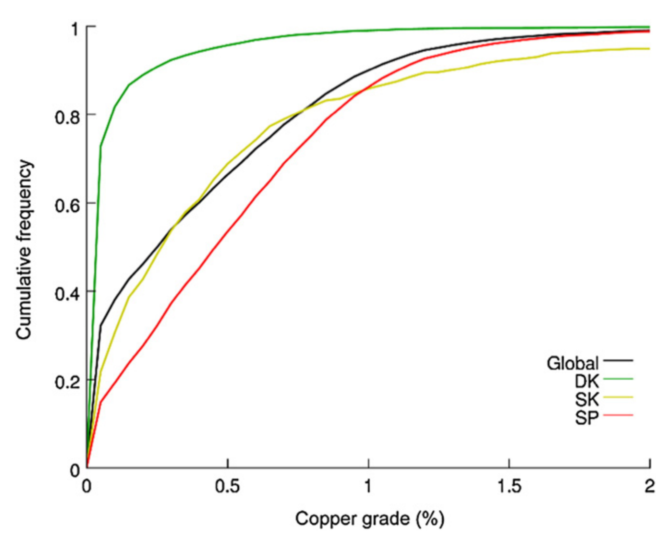

Fig. 2. Cumulative frequencies of copper grades, for the entire deposit and for each rock type domain.

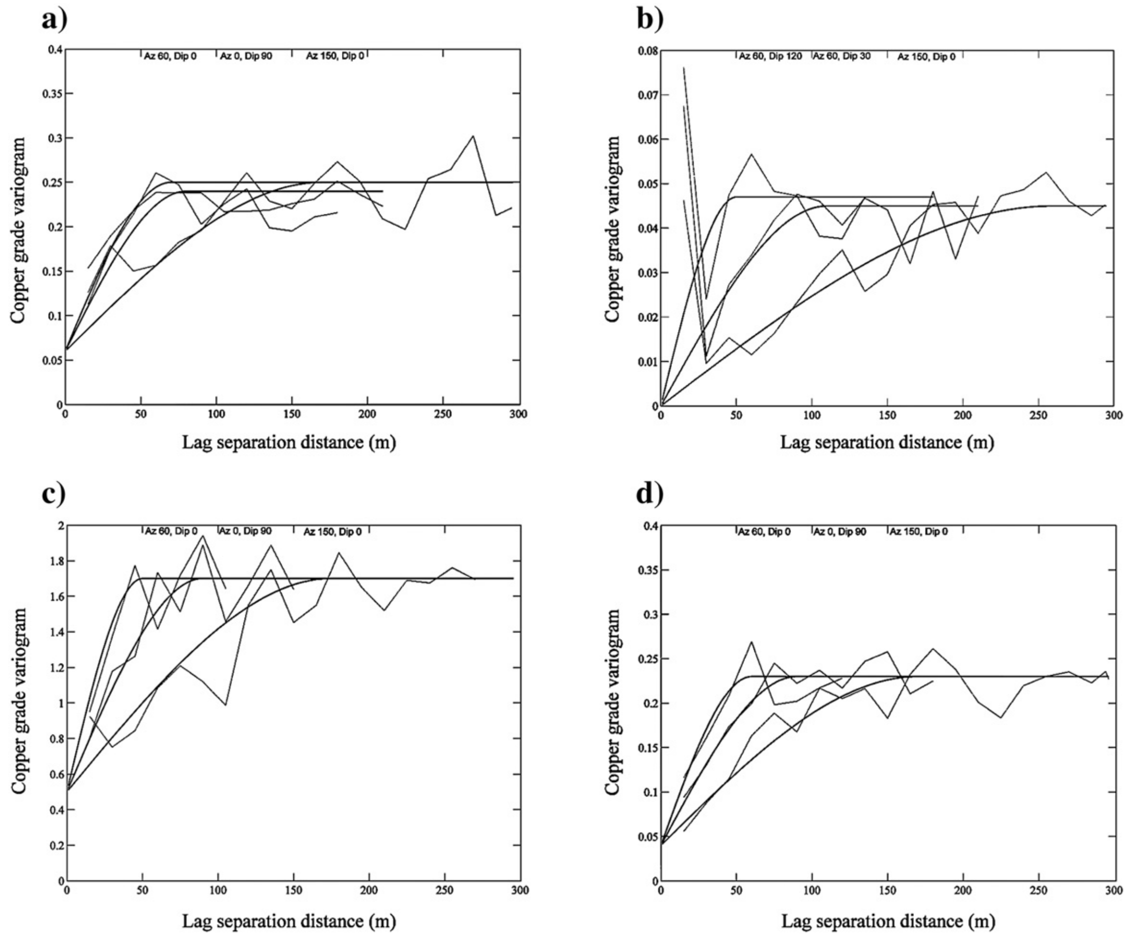

Fig. 3. Experimental (dotted lines) and modeled (solid lines) variograms of copper grades, for a) the entire deposit, b) DK domain, c) SK domain and d) SP domain.

Gaussian random fields $\{Y_1, Y_2\}$ and two thresholds $\{y_1, y_2\}$ are used for constructing the truncation rule (Fig. 4): the second random field (Y_2) is used to distinguish the two oldest domains (SP and SK), which have an approximately similar anisotropy and irregular boundary, while the first random field (Y_1) is used to erode these two domains by the late-injected dykes that have no economical mineralization. These dykes have more regular boundaries with the other two domains. Accordingly,

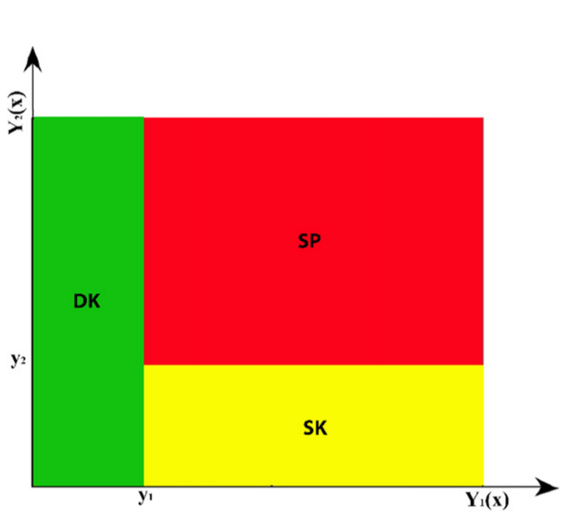

Fig. 4. Two-dimensional flag indicating the truncation rule used for converting Gaussian values into rock type domains in Sungun deposit.

the rock type prevailing at a given spatial location **x** is defined in the following condition:

- location **x** belongs to DK domain $\Leftarrow\Rightarrow Y_1(\mathbf{x}) < y_1$
- location **x** belongs to SK domain $\Leftarrow\Rightarrow Y_1(\mathbf{x}) > y_1$ and $Y_2(\mathbf{x}) < y_2$
- location **x** belongs to SP domain $\Leftarrow\Rightarrow Y_1(\mathbf{x}) > y_1$ and $Y_2(\mathbf{x}) > y_2$.

The truncation thresholds $\{y_1, y_2\}$ can be calculated in order to reproduce the domain proportions (Emery, 2007; Armstrong et al., 2011).

The variograms of the Gaussian random fields are then determined through their impact on the variograms of the domain indicators, by trials and errors (Emery, 2007; Armstrong et al., 2011). Fig. 5 shows the sample and modeled indicator variograms for each domain, while Table 2 indicates the parameters for the variograms of the Gaussian random fields. In order to reproduce the regular boundary between late-injected dykes and the other two domains, cubic variogram models have been used for the first Gaussian random field (Y_1) since they are smooth at the origin and associated with regular boundaries. In contrast, spherical models (linear at the origin) are used for the second Gaussian random field, which will produce a more irregular boundary between domains SK and SP.

Provided with the model parameters and the conditioning data (drill hole data), the rock type domains are simulated using a publicly available code (Emery, 2007). Specifically, 100 realizations are obtained on a grid with spacing of 5 m along the east–west and north–south directions and of 2 m vertically. As an illustration, Fig. 6 depicts four realizations over the same cross-section as in Fig. 1. In turn, Fig. 7 shows the probability maps for the three domains calculated with the

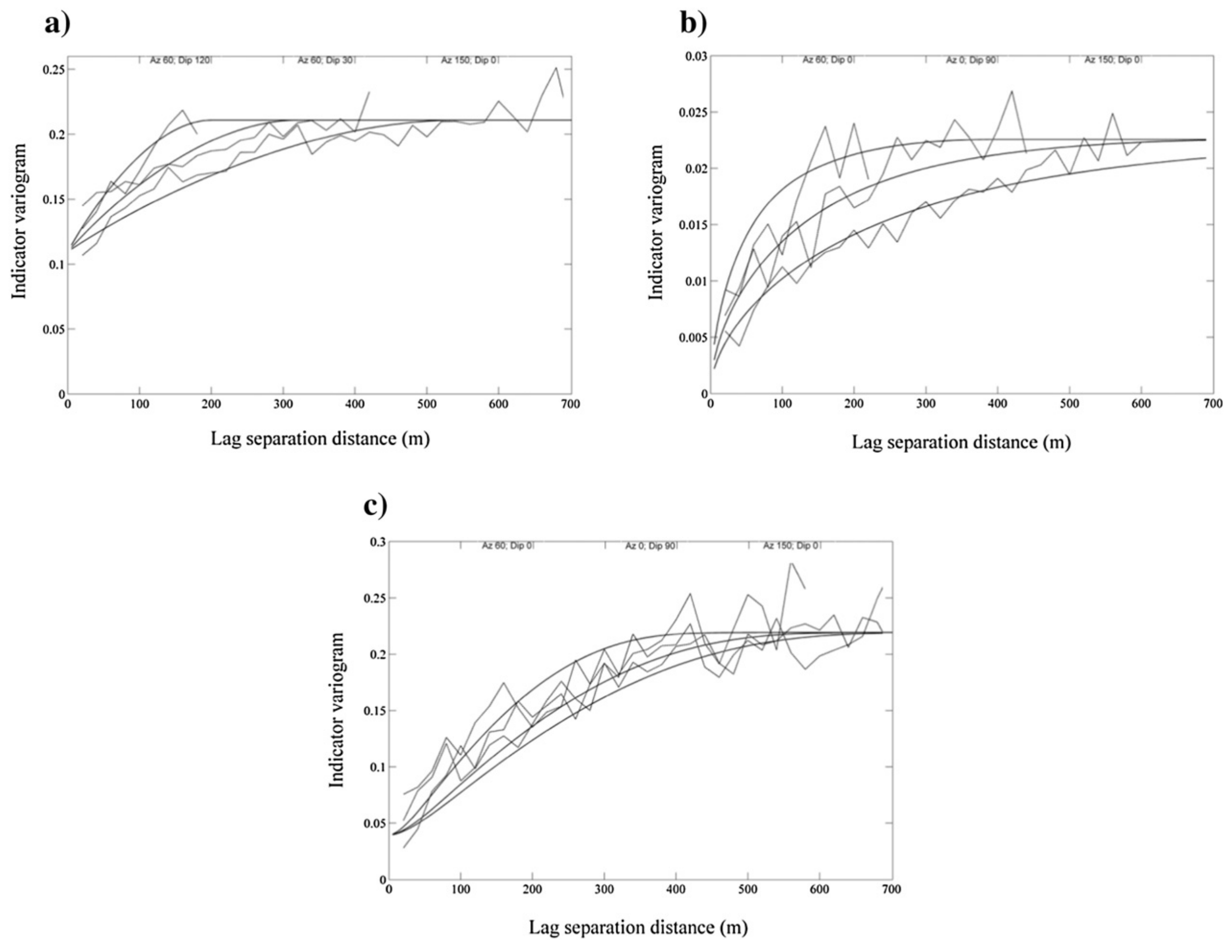

Fig. 5. Experimental (dotted lines) and modeled (solid lines) indicator variograms along the main anisotropy directions for a) DK domain, b) SK domain and c) SP domain.

100 realizations so obtained. In these maps, the red regions correspond to locations where there is little doubt to find a specific rock type domain, while the regions painted in blue correspond to locations where domains are quite unlikely to be present. Both red and blue regions are located around the drill holes, for which the domains have been observed directly (geological logs). Finally the intermediate color regions indicate a greater uncertainty on whether or not a specific domain can be found (in particular, whether or not there is some economic mineralization). These mainly correspond to the regions in-between the drill holes.

2.3. Application to improve mineral resources evaluation

At present, the most common approach for incorporating the geological information in the grade model, is to deterministically divide the deposit into rock type domains (based on drill hole data and expert mine geologist) and to predict the grades within each domain independently, e.g., via kriging. Fig. 8a depicts the deterministic interpretation of the rock type domains in Sungun copper deposit, for the same cross-section as in Figs. 1 and 6. According to this deterministic interpretation, each mineable block will belong to a certain rock type domain.

This approach hypothesizes that the grades in a given domain are isolated from the other domains, and because of this assumption the obtained grade model strongly depends on the mine geologist interpretation about the layout of the domains and boundaries between them. As a result, one usually obtains a grade model with clear-cut discontinuities when passing from one domain to another one (Fig. 8b). These discontinuities do not agree with what really happens in Sungun porphyry copper deposit: according to the mine geologists and production data, the copper grade changes gradually when passing from one domain to another.

To account for the uncertainty in the layout of rock type domains (not considered in the deterministic approach) and to produce gradual boundaries in the grade model when passing from one domain to another, a more sophisticated approach is proposed, based on the probability maps shown in Fig. 7. This approach consists in weighting the grades that are predicted in each rock type domain independently by the probability of occurrence of this domain (Emery and González, 2007a, 2007b) (Fig. 8c). A consequence of such a weighting is that the finally predicted copper grades change gradually when crossing the boundaries between rock type domains (Fig. 8c).

Another shortage of the deterministic approach is that the interpretation of rock type domains is unavoidably related to the preconception of the mining geologist about the spatial distribution of geological domains and is subject to simplification, in particular, in relation to the complicated structure of the late-injected non-mineralized dykes. Deterministic interpretations are therefore likely to misclassify the rock type domains when geology gets complex. The errors in the rock

Table 2
Parameters for the variogram models of the Gaussian random fields.

Gaussian random field	Nugget	Sill	Basic structure	Longer range (m)	Middle range (m)	Shorter range (m)	Azimuth (°)	Dip (°)
Y_1	0.05	0.40	Cubic	200	120	80	150	30
		0.55	Cubic	800	600	250		
Y_2	0	0.38	Spherical	350	250	110	150	0
		0.62	Spherical	1350	950	640		

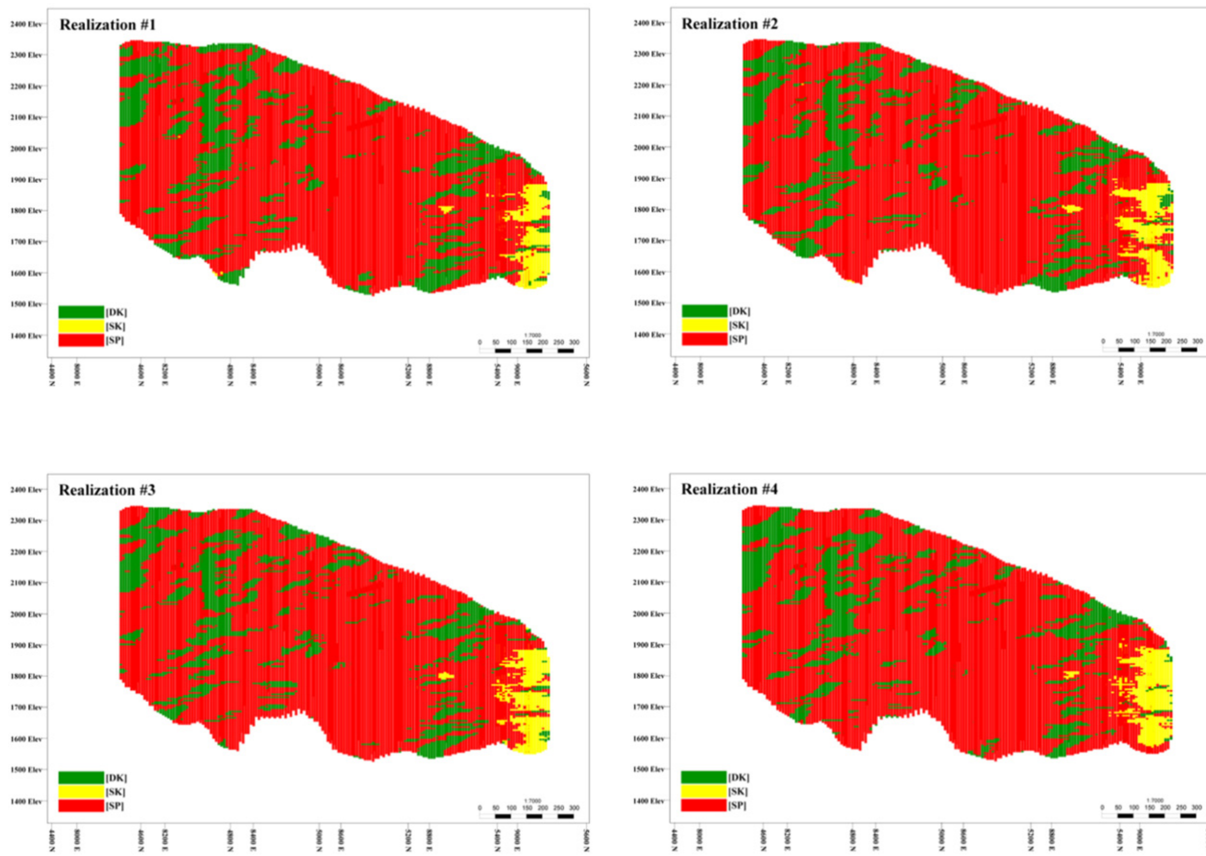

Fig. 6. Four conditional realizations of the rock type domains.

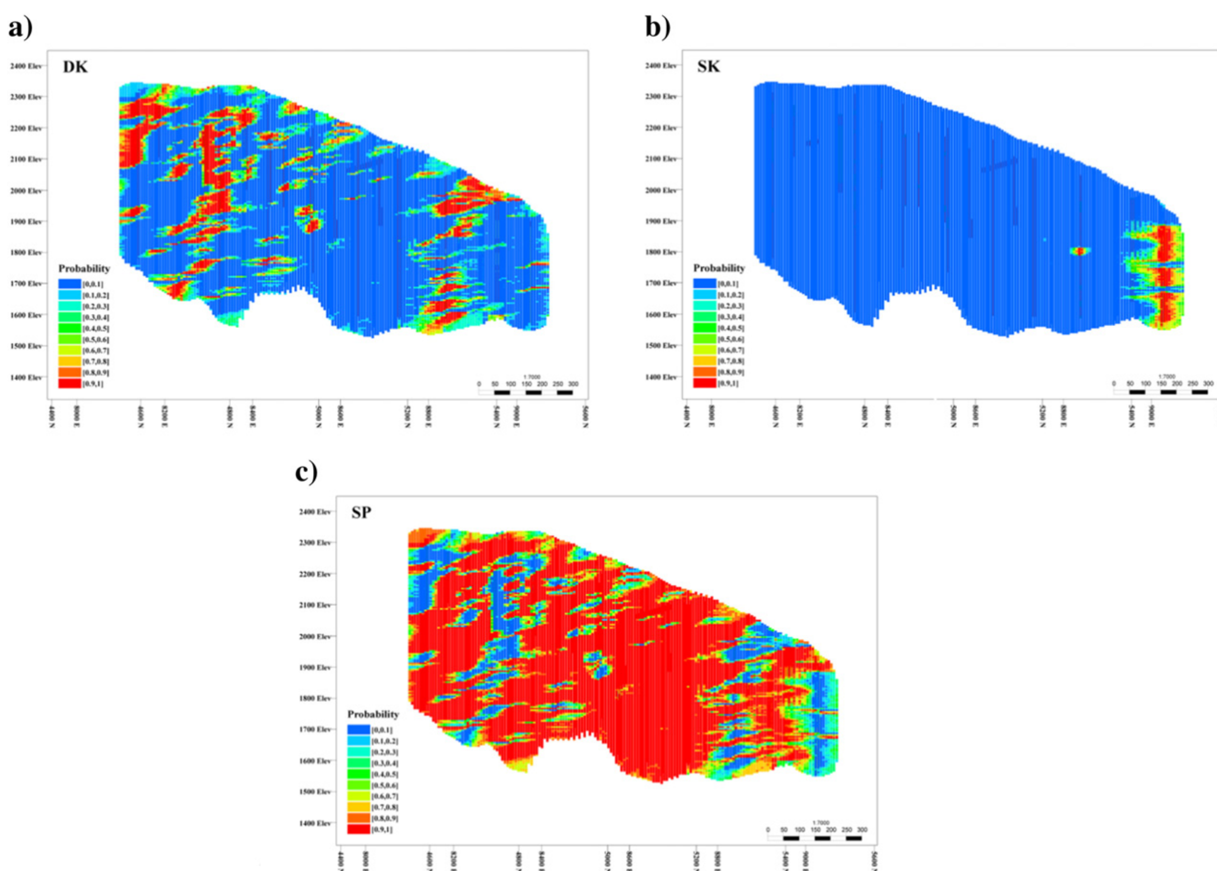

Fig. 7. Probabilities of occurrence of rock type domains, obtained from a set of 100 conditional realizations.

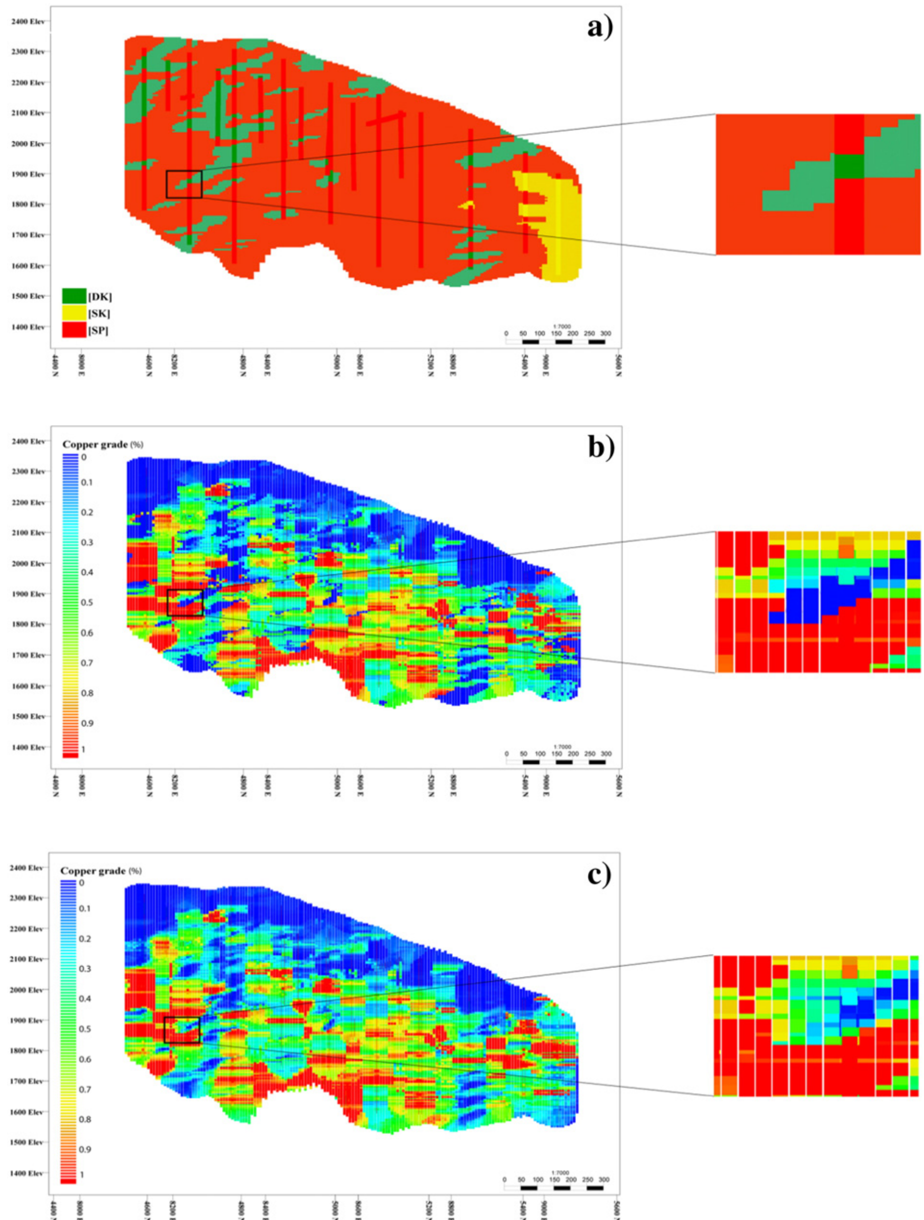

Fig. 8. a) Deterministic model of rock type domains. Copper grade models obtained by using a deterministic (b) and a stochastic (c) modeling of the rock type domains.

type model affect the predicted grades and tonnages, and mutually all the future mining plans. In contrast, the stochastic approach for modeling rock type domains produces a grade model that accounts for the uncertainty in the spatial layout of domains and exhibits a smoother grade map. This smoothing effect is inevitable because the aim of this study is to make the grade prediction more accurate, avoiding misclassifications between dykes that have no economic mineralization and porphyry and skarn that have a different grade distribution model.

Table 3
Performance comparison between the two approaches for copper grade prediction. The statistics are given for the entire validation set (11,450 blast holes).

	Modeling grade based on deterministic rock type model	Modeling grade based on stochastic rock type model
Correlation between true and predicted grades	0.863	0.907
Mean error	0.0009	0.0009
Mean absolute error	0.1022	0.0812
Mean squared error	0.0290	0.0191

2.4. Performance evaluation

The grade models based on deterministic and stochastic rock type modeling are validated against 11,450 production data (blast hole data) located in several benches of the Sungun mine. The main statistics on the prediction errors and the correlation coefficients between the actual and predicted grades at the blast hole locations are presented in Table 3. Overall, the approach based on a stochastic rock type modeling gives a more accurate prediction, as it decreases the mean absolute and mean squared errors in comparison with the other approach and improves the correlation coefficient between predicted and true grades.

3. Conclusions

Deterministic interpretation of the main geological domains, based on drill hole data and expert knowledge, is an essential approach for the comprehension of the deposit genesis, for resources and reserves evaluation, also for mine planning and mineral processing. However, this approach is logically unable to reproduce the true spatial variability and to measure the uncertainty in the domain layout, which may produce a significant error in the grade models. As an alternative to this approach, this study focused on a stochastic modeling of geological domains, using geostatistical simulation, and on the calculation of probabilities of occurrence of each domain over the area of interest. These probabilities are subsequently used for weighting the grade prediction associated with each domain so as to obtain the final grade model.

In Sungun porphyry copper deposit, the dyke domain has no economic mineralization and should not be considered in the mineral resource evaluation step, while the porphyry and skarn domains have different copper grade distribution models and should be separated from each other in the resource/reserve evaluation step. In this study, the plurigaussian model has been used to simulate these rock type domains. This model allows accounting for different spatial continuity patterns of the domains (in particular, different spatial anisotropy directions for the non-mineralized dyke in comparison with the other domains), incorporating geological knowledge (drill hole data) and also reproducing the topological contacts between domains to make the results more realistic from a geological point of view. The stochastic approach modified the clear-cut discontinuities of the traditional approach and reproduced the soft boundary in grade model that agrees with the geology of the deposit. The validation against production data showed the improved accuracy of the proposed method in contrast with the traditional approach.

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