Geological modeling by an indicator kriging approach applied to a limestone deposit in Indiara city - Goiás

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Abstract

The mineral exploration activity consists of a set of successive stages that are interdependent on each other, in which the main goal is to discover and subsequently evaluate a mineral deposit for the feasibility of its extraction. This process involves setting the shape, dimensions and grades for eventual production. Geological modeling determines the orebody's possible format in subsoil, which can be done by two approaches: vertical sections (deterministic methods) or geostatistical methods. The latter approach is currently being preferred, as it is a more accurate alternative and therefore, more reliable for establishing the physical format of orebodies, especially in instances where geologic boundaries are soft and/or with widely spaced sample information. This study uses the concept of indicator kriging (IK) to model the geologic boundaries of a limestone deposit located at Indiara city, Goiás State, Brazil. In general, the results indicated a good adherence in relation to samples. However, there are reasonable differences, particularly in lithological domains with a small number of samples in relation to the total amount sampled. Therefore, the results showed that there is a need for additional sampling to better delineate the geological contacts, especially between carbonate and non-carbonate rocks. Uncertainty maps confirmed this necessity and also indicated potential sites for future sampling; information that would not be obtained by usage of deterministic methods.

Keywords: mineral exploration, modeling, indicator kriging, uncertainty.

1. Introduction

A mining project consists of a set of successive and interdependent stages, culminating or not in mineral deposit exploitation. It begins with an exploration phase classified into several consecutive and interconnected stages. According to its progress, this phase involves increases in spending and decreases in associated geological risk (Moon and Whateley, 2006).

Characterization of the mineralized zones and surroundings are controlled by the knowledge of their internal characteristics, which are understood with sampling and surface outcrop analyses. These provide infor-

mation for the deposit's detailed assessment, known as delineation (Sinclair and Blackwell, 2004); this step is also called geological modeling by authors such as Rossi and Deutsch (2014).

A geologic model can be obtained through various approaches. The traditional one is based on the interpretation of geological variables in cross sections and planning maps, where such interpretations are extended to three-dimensional solids. This process is called *deterministic geological modeling,* since it does not involve quantifying the uncertainty associated with the model. Another approach that

is particularly used when data is too widely spaced to reliably delineate the model, is to obtain a geologic model from mathematical methods (polygons or nearest neighbor), or geostatistical ones that can follow two treatments: (i) a deterministic model that estimates the category in each location; and (ii) a model that gives the probability of each category occuring in each location within the deposit or domain (Rossi and Deutsch, 2014).

Limitations in traditional geological modeling (i.e. deterministic methods) have motivated the use of geostatistical techniques to improve the

characterization of geological domains and reduce uncertainty about geological contact positions. One of these techniques is indicator kriging (IK) (Emery and González, 2007). Indicator-based techniques that involve the linking of an indicator to each geological attribute (i.e. geological domain), provide the probability of each geological variable to be present at each unsampled location (Rossi and Deutsch, 2014). From this information (probability), it is possible to establish the uncertainty, treated also by simulation techniques. This matter can be found, among others, in the works of Souza and Costa, (2013) and Yamamoto *et al.*, (2015).

Herein the indicator kriging approach was used for the geological modeling of a limestone deposit located in the city of Indiara, State of Goiás, Brazil. The Calcário Ouro Branco and Fillercal companies, belonging to the Pirineus business group that owns the mining rights on site, provided the data used. The purpose of this article is to apply a geostatistical method approach (indicator kriging) to geological modeling to propose an alternative geologic model for the mining enterprise.

2. Study Area

The study's site is located approximately 15 km from Indiara's city center, along the BR-060 margins, towards Goiânia, the capital of Goiás State. The samples collected, provided by Calcário Ouro Branco and Fillercal, were taken from the current Francisco Pereira mine, with its approximate coordinates being 17°7'45.87"S and 49°52'13.85"W (Figure 1). The enterprise, Pirineus group, has administrative installations, mineral processing and storage facilities, and three mines in operation, each of them mined using the open pit method.

Calcário Ouro Branco has an infrastructure for producing agricultural limestone, while Fillercal has one for fiber cement, animal feed, texture, fine and superfine production lines; the last two apply to the paint industry. Predominantly, current extraction takes place in the Francisco Pereira mine, which is the area to be analyzed herein.

The current mine (Francisco Pereira) was established from a mineral reserve based on estimates realized by the Inverse Squared Distance (ISD) method. The geologic model was previously obtained by the company through the method of vertical sections (union of geological sections to form three-dimensional solids), a model that did not adequately reproduce the geological bodies.

The local site, according to Figure 1, belongs to the Anicuns-Itaberaí Sequence. Studies from Lacerda Filho *et al.*, (1999), Pimentel *et al.*, (2000), Barbosa, (1987) apud Laux, (2004), Laux *et al.*, (2001, 2002) apud Laux, (2004), Laux *et al.*, (2010), Hasui, (2012) and Navarro *et al.*, (2015) indicate that the Anicuns-Itaberaí Sequence (890-830 Ma) is a metavolcano-sedimentary sequence, neoproterozoic, belonging to the Goiás Magmatic Arc. This sequence is exposed along the contact between the eastern part of Goiás Magmatic Arc and the Anápolis-Itauçu high-grade terrain, and is represented predominantly by amphibolites and metapelites, with iron formations, cherts, marbles and ultramafic rock subordinations. There is also a presence of limestone and marble lenses interlayered with schists.
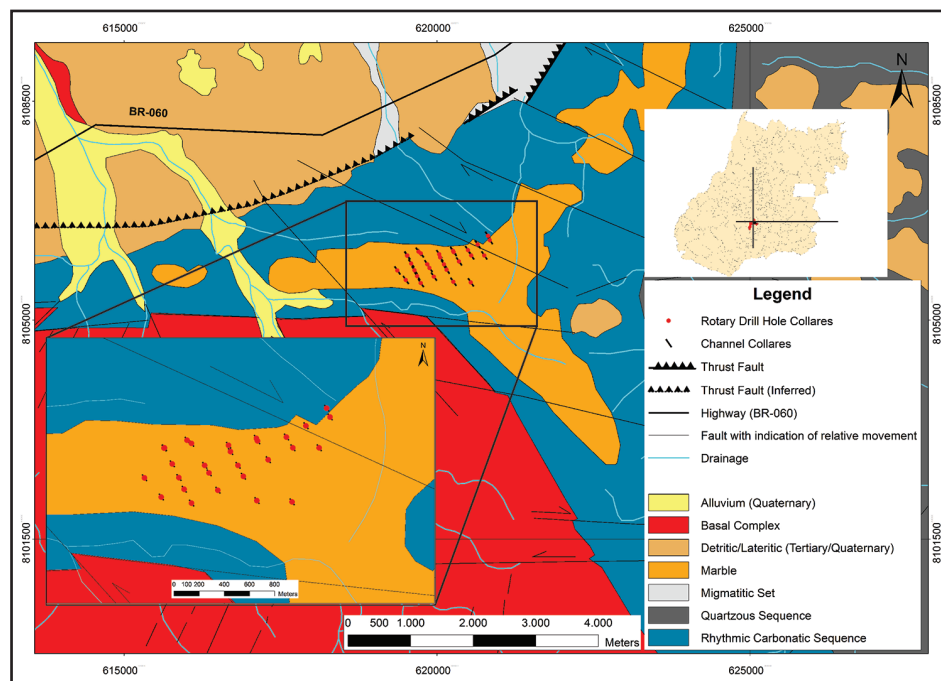

Figure 1
Study area location and position of the samples (Modified from Araújo *et al.,* 1980 referenced Fumes, 2014).

3. Materials and methods

The sampled data consisted of 455 samples obtained from 15 rotary drilled holes and 13 trenches/channels, with a predominant sample length of 5 m, coincident with the average bench height of the current mine geometry. The drillhole samples are arranged in a grid with an average spacing of 230m x 200m, oriented to NE and SE, respectively. Available analytical data – CaO and MgO grades – are derived from X-ray fluorescence chemical analysis. Moreover, the Pirineus group also provided a geological description of the drillhole samples. Based on existing sampling, it was decided to use the channel data aiming at

a quantitative information improvement.

The sampled data were first submitted to validation and similarity analyses, comparing analytical results with their geological descriptions; the latter being primordial in supporting the classification of lithological domains.

Information concerning company-adopted classification for its products, mainly chemical (CaO and MgO), amongst the carbonate rock classifications proposed by Machado (2016), was used as basement for the lithological unit classification (Table 1). The domains were

classified as Calcitic Limestone (CLC), Magnesium Limestone (MAG), Dolomitic Limestone (DOL), Impure Limestone (CLI) and Volcanic or Metavolcanic (VMV). The last two represent limestone interlayered non-carbonate rocks and non-carbonate rocks respectively.

Table 1
Classification criteria
for lithological unities/categories.

Domain/Category	Chemical Criteria
CLC	Impurity < 25%, CaO + MgO > 38% and MgO < 5%
MAG	Impurity < 25% CaO + MgO > 38% and MgO ≥ 5% and MgO ≤ 12%
DOL	Impurity < 25%, CaO + MgO > 38% and MgO > 12%
CLI	Impurity ≥ 25% and ≤ 50%
VMV	Impurity > 50%

A statistical analysis of both variables was performed on each unit to learn about the statistical distribution of each and verify the presence of outliers. This analysis identified two outliers, both in the DOL unit, which

were removed. Therefore, subsequent steps were carried out on 453 samples.

Lithological domains were coded and then their indicator variables were elaborated, one for each unit. In this step, a value of 1 was assigned to in-

dicate the presence of a domain, and 0 to indicate the unit absence. For the lithological domain LDi at location x, the indicator variable transformation was performed according to the following equation:

$$I_i(x) = \begin{cases} 1 \ if \ x \in LD_i \\ 0 \ otherwise \end{cases} \quad (1)$$

Where i, in this case, varies from domain 1 to domain 5.

For each indicator variable, three semivariograms were calculated and modeled; two in the XY plane, that is, a horizontal plane, and one in the vertical plane, that is, with a 90° dip. Such step is fundamental because it quantifies the geological continuity of each lithological

domain. All experimental semivariogram model fittings (Figure 2) were performed by a simple spherical structure, except for the indicator variable assigned to the dolomitic limestone domain, whose fitting was performed by two spherical structures. Table 2 shows the indicator semivariogram parameters for each domain.

The ik3d resulting model was re-

fined in SGeMS by a script to calculate: (i) the highest probability – between five probabilities – at each point estimate and assign to this value, the corresponding domain code; and (ii) the uncertainty associated with the estimate, calculated as the subtraction between the maximum probability (one) and the highest probability.

Table 2
Indicator semivariogram
parameters for each domain/category.

Domain	Direction	Nugget Effect	Structure 1			Structure 2		
			Model 1	Sill	Range (m)	Model 2	Sill	Range (m)
CLC	Azimuth 60°	0.13	Spherical	0.12	339.84	-	-	-
	Azimuth 150°				161.2			
	Vertical				31.875			
MAG	Azimuth 60°	0.047	Spherical	0.093	305.00	-	-	-
	Azimuth 150°				210.00			
	Vertical				20.00			
DOL	Azimuth 60°	0.020	Spherical	0.030	406.6	Spherical	0.043	21.40
	Azimuth 150°				252.56			72.16
	Vertical				4.62			15.84
CLI	Azimuth 60°	0.032	Spherical	0.059	613.20	-	-	-
	Azimuth 150°				137.50			
	Vertical				7.68			
VMV	Azimuth 60°	0.02	Spherical	0.08	310.00	-	-	-
	Azimuth 150°				235.62			
	Vertical				9.91			

Figure 2
Experimental semivariograms for indicator variables and their respective model fittings.
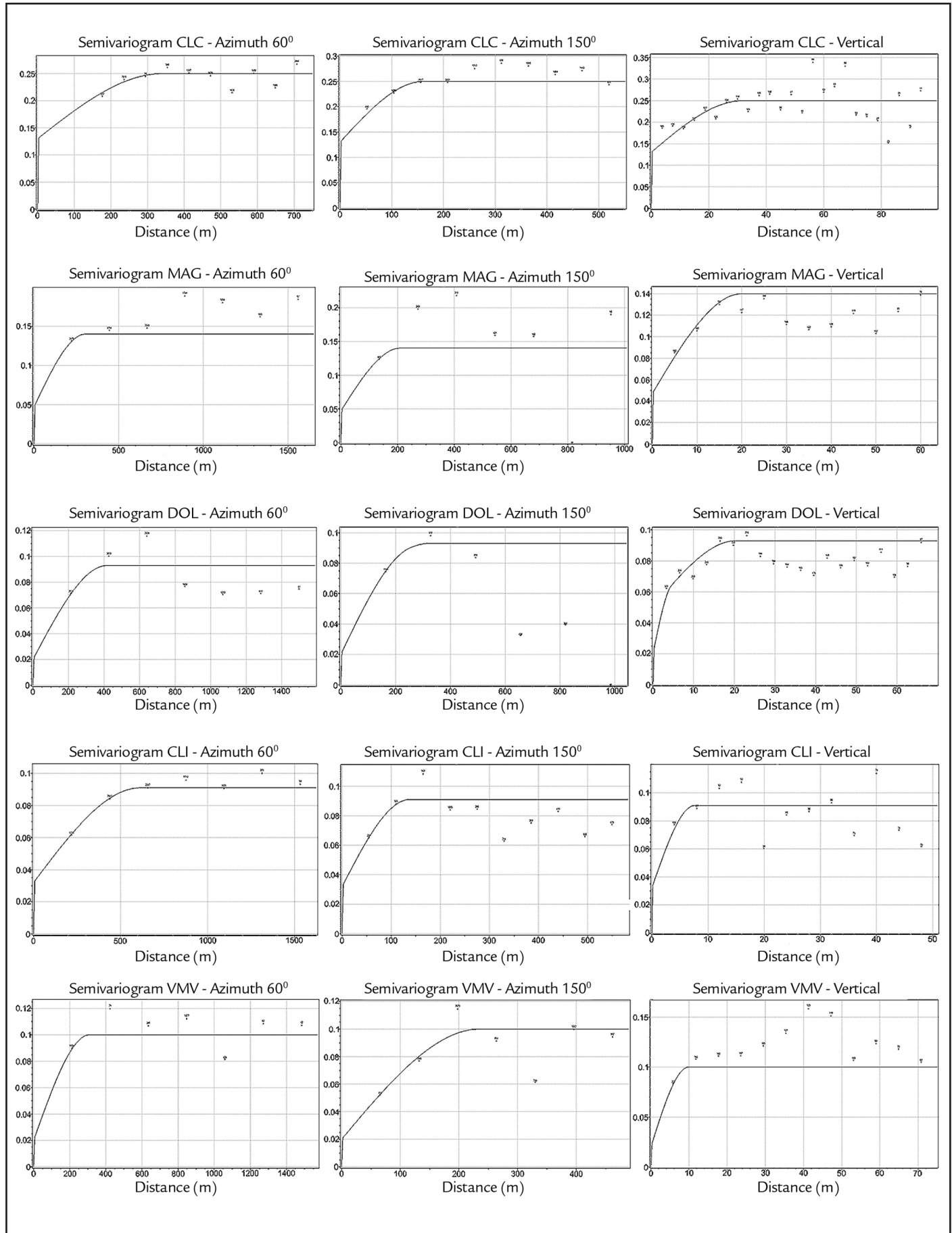
The estimates of the probabilities by indicator kriging were made from a block model with 10 m x 10 m x 5 m dimensions. These dimensions were defined on X and Y in order to have a higher detail level in the geological contacts. The value used is close to half the width of the blocks in the current mine's geologic model (25 m). The block dimension in Z was chosen this way for being: (i) the most frequent sample length value; (ii) less than all ranges in the semivariograms; and (iii) a multiple of the current bench height (10 m).

The information contained in the resulting geologic model demonstrates: probability of occurrence in each domain – estimated by indicator kriging; domain code with the highest probability of occurrence; and uncertainty.

4.Results and discussions

Comparative analysis in each geological model cross section between estimated lithological domain and sample lithological domain evidences good concordance between them. Thus, in general terms, the probabilistic approach was efficient in describing orebody shapes. Moreover, the limestone rocks are installed in the Anicuns-Itaberaí metavolcano-sedimentary sequence (neoproterozoic) in the form of lenses. Structurally, these lenses are positioned on the flank of a large anticline whose axis plunges gently to the west. In the geological model generated by indicator kriging, the geometry of the calcareous bodies is compatible with the geometry of the local geology of the limestone lenses. Figure 3 shows an example of a cross section with the block model obtained by indicator kriging and the samples.
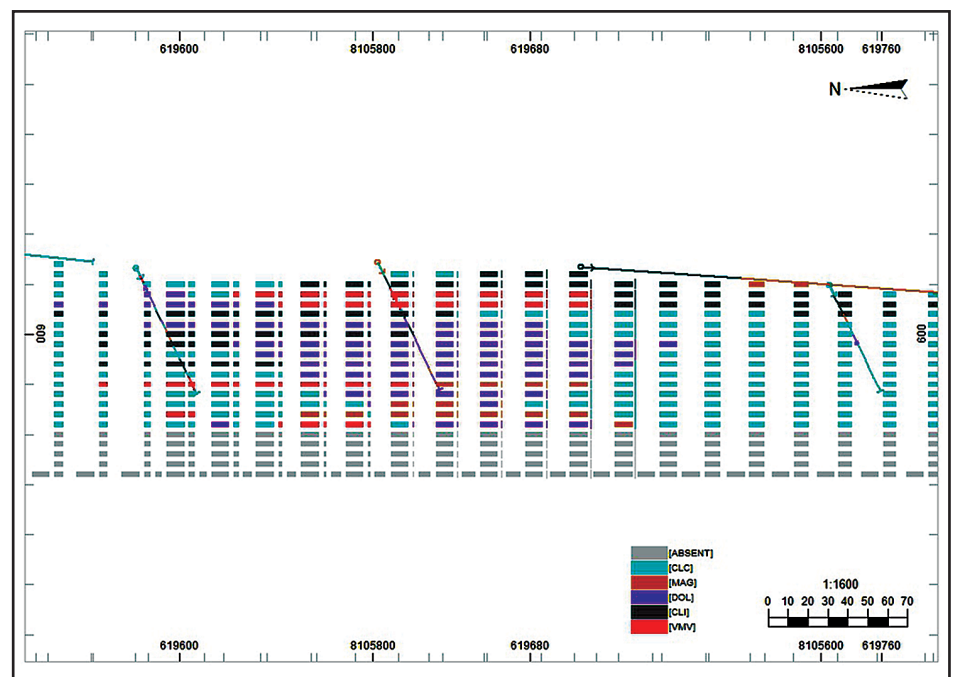

Figure 3
Example of a cross section with comparison between lithological domains of the samples and the block model.

When comparing sample proportions/relative frequencies with respective proportions obtained by the probabilistic model (Table 3), there was supposedly an overestimation of the CLC domain, while the remaining domains are apparently underestimated. The differences between estimated and sampled domains are higher in units with small relative frequencies, in both the probabilistic geological model and sampling. The biggest difference is assigned to the CLI domain, whose modeled relative frequency was 50% lower than the sampled relative frequency/proportion. By calculating the average deviation from the sample data, it has been observed that the model proportions, on average, differ 23.7%, negative, from the sample proportions.

Differences between the probabilistic model and the observed reality (samples) can be a consequence of the semivariogram models used, which showed high values of the Nugget Effect, mainly due to the small amount of data available. By increasing the amount of samples, particularly in areas with high incidence of geological contacts – between carbonate and non-carbonate rock – there might be a substantial improvement in the geologic model.

Table 3
Deviations between probabilistic model and sample proportions/relative frequencies.

Domain	Proportions		Difference (%)
	Samples	Model	
CLC	0.51	0.71	+39.2
MAG	0.17	0.10	-41.2
DOL	0.10	0.07	-30.0
CLI	0.10	0.05	-50.0
VMV	0.11	0.07	-36.4

Three-dimensional mapping of the uncertainties indicates a need to conduct additional sampling to achieve a more reliable delineation of geological contacts. Such additional sampling would be required even in the mine operation area, as seen in the Figure 4 example, which shows a cross section perpendicular to operaíion benches. It is observed in this section that uncertainty levels reach 71%.
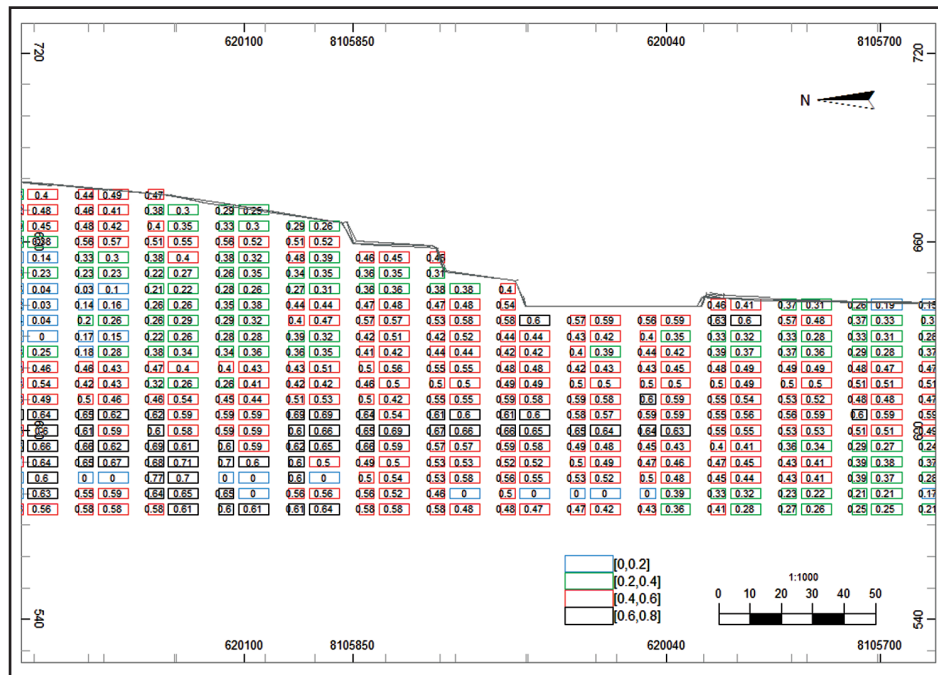

Figure 4
Example of a geologic model cross section with values of uncertainty, which represents the uncertainty in geologic delineation.

5. Conclusions

The indicator kriging geological modeling approach has proved more efficient than the traditional cross section method, since it allows more consistent elaboration of the model, especially in limited sample information cases. In such situations the establishment of geological continuity between sections is an interpretative task, very dependent on the professional's prior knowledge. Moreover, it is speculative, since it is based only on subjective inferences, often based on scarce evidence.

The comparative analysis of the resulting geologic model against the observed reality (i.e. samples) demonstrated a reasonable deviation, particularly in the less proportionately significant lithological domains (MAG, DOL, CLI and VMV). This fact is partially a consequence of the widely spaced sampling grid used (230 m x 200 m) that was insufficient for describing geological variations at smaller scales and provide semivariogram models with smaller Nugget Effects. Therefore, it is suggested that additional samples be collected in order to refine the resulting model.

The uncertainty model allowed the establishment of sites with high geological risk. This provides guidelines for future sampling programs to define geological contacts with more accuracy, particularly between carbonate and non-carbonate rocks. The information about uncertainty and a non-subjective modeling, based on geological continuity quantification (semivariograms), are the differential of this approach, particularly when widely spaced samples are available. Moreover, uncertainty quantification would not be obtained from the traditional cross section method.

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