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 geological 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.
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.

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
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 indicate 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:

\[
I_i(x) = \begin{cases} 
1 & \text{if } x \in LD_i \\
0 & \text{otherwise}
\end{cases}
\]

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 refined 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 | Model 1 | Sill | Range (m) | Structure 1 | Sill | Range (m) | Structure 2 |
|--------|-----------|---------------|---------|------|-----------|-------------|------|-----------|-------------|
| 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 | - | - | - |
|        | Vertical | - | - | 4.62 | - | - | - |
| 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.

| Domain | Proportions | Differences (%) |
|--------|-------------|-----------------|
| 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 |

Table 3
Deviations between probabilistic model and sample proportions/relative frequencies.
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 operation benches. It is observed in this section that uncertainty levels reach 71%.

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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