USING GEOLOGIC MODELS TO SUPPORT RESOURCE AND RESERVE ESTIMATION OF MARBLE DEPOSITS IN COMPLEX SETTINGS

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ABSTRACT
The marble deposits operated by Cementos Avellaneda S.A. in the Sierra del Gigante, approximately 100km NW of the city of San Luis, Argentina, are complex, folded and fractured deposits with varying marble quality. In addition to the challenge of modelling the complex geology, the resource and reserve estimation of the deposit has to take into account the chemical composition of the rock and the effect it causes on the processing kilns.

The use of a detailed geologic model is considered paramount for an accurate prediction, but at the same time the modelling has to represent as accurately as possible those aspects that are most consequential to kiln performance. In this sense, the geologic variables of interest are somewhat different from those interpreted and modelled for exploration purposes.

The detailed geological modelling of the folded structures presents many challenges and is difficult to do using software tools alone. The interpretation and evaluation of the model behaviour requires careful analysis and adjustments by smoothing the different contacts in the global model.

The geostatistical methods used in the estimation of the resources have to take into account the complex geometry and the zonation of quality variables of marble. While the contacts with non-marble rock tend to be hard contacts, within the marble itself the properties of interest evidence more or less smooth transitions that should be accurately modelled.

The objective of this paper is to raise awareness of potential modelling difficulties in seemingly simpler mineral deposits. The paper specifically discusses the intricacies of modelling marble deposits in complex settings and the impact of quality variables in kiln performance. A discussion and work path for future improvements to the modelling effort is suggested.

INTRODUCTION
The deposit is located in the Sierra del Gigante (Figure 1), 100km northeast of the city of San Luis in central-west Argentina. There are several individual deposits, the most important ones being Cerro Redondo, Cerro La Calera, and Cerro Impuro II.

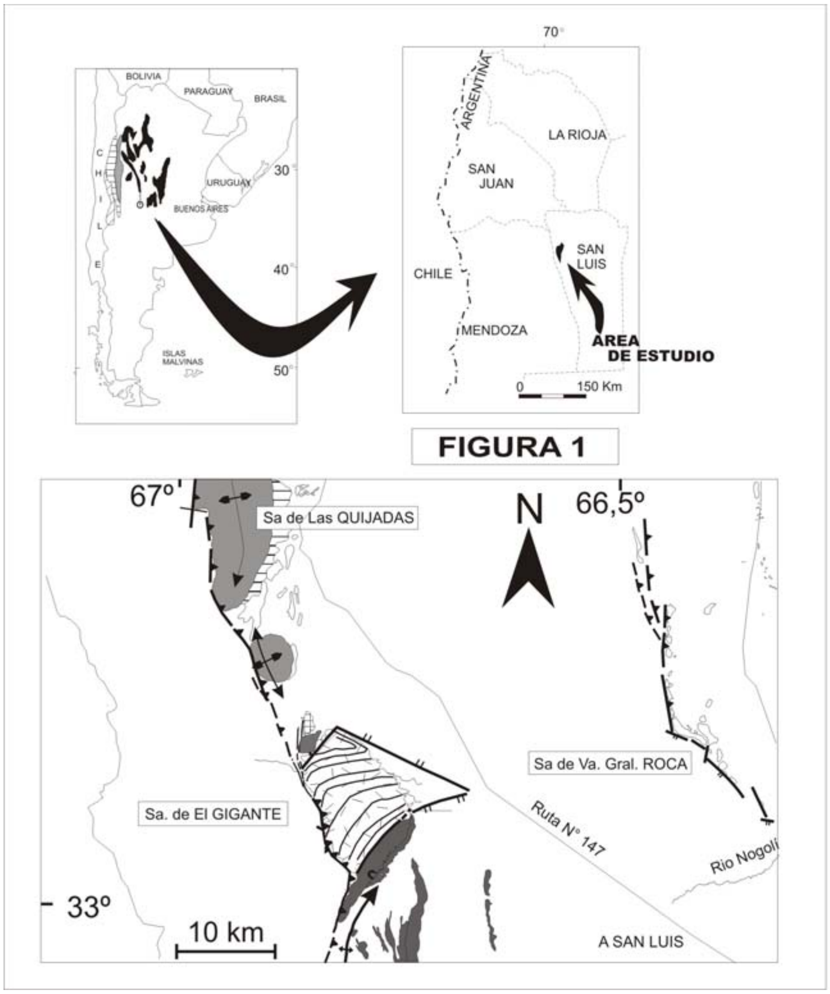

Figure 1: Location map

The operating company (Cementos Avellaneda S.A.) applies three-dimensional resource models, obtained after careful geologic modelling and geostatistical grades estimation for each mined deposit. From these, the reserves are estimated, as well as the materials to be consumed during the process and the implementation of the long-term (10 year horizon) and short-term (1 year horizon) mine plans.

The short-term mine plan is fed back iteratively with assays' results from blast holes. The samples are obtained after proper reduction and splitting of the material collected from drilling 10m benches.

The long-term model in particular is a reasonable representation of the carbonate content of the mined material, but it does not perform well at predicting contaminants into the processing kilns. This paper analyses the differences between the long and short-term models in relation to their impact into mine planning and mine operation. The combined use of the geologic and geostatistical models, in addition to the blast hole data, allows for an improved prediction of the material that is loaded onto the homogenisation stockpile.

GEOLOGIC DESCRIPTION OF THE DEPOSITS

The marble deposits belong to the El Gigante metamorphic complex [1, 2], comprised of an alternating sequence of schists and marble with minor intercalated quartzite and amphibolites, which are more dominant on the North and Central areas of the mountain range (Figures 2 and 3).

Figure 2: Marble outcrop illustrating the degree of deformation commonly found in the area

Figure 3: Mica-schists, abundant in the Northern part of the El Gigante mountain range

The metamorphic rocks are a result of pressure and temperature, after which significant deformation at different stages produced folding and overturning of the entire sequence. As a consequence, a series of tight, asymmetrical geometries were generated with isoclines oriented on average to the South, with an axis dip to the East. There is also a significant disharmony between the schist and marbles due to their rheological contrast, and in addition, the amphibole bodies add more complications.

An additional issue to consider is that the marble's ductility complicates the understanding and interpretation of their geometries because deformation and metamorphism produce stretching and thickening of the isoclinals' hinges (Figure 4).

Figure 4: Details of a fold in the Northern area of the Sierra

The marble's sequence, particularly towards the North, is relatively homogeneous, with 70° to 100° azimuth. The relative hardness of the marble with respect to the schists explains the morphology of the area, such as the hills that are currently being mined.

Folding generates designs in S, Z, and M shapes, with the first one being the most common in the mine areas. Figure 5 shows the crest of the Central area.

With the deformation model and field work to confirm and detailed mine-scale observations to obtain, a final deformational model was developed for the entire district, applicable to the interpretation of the marble layers and sequences, which was done on sections.

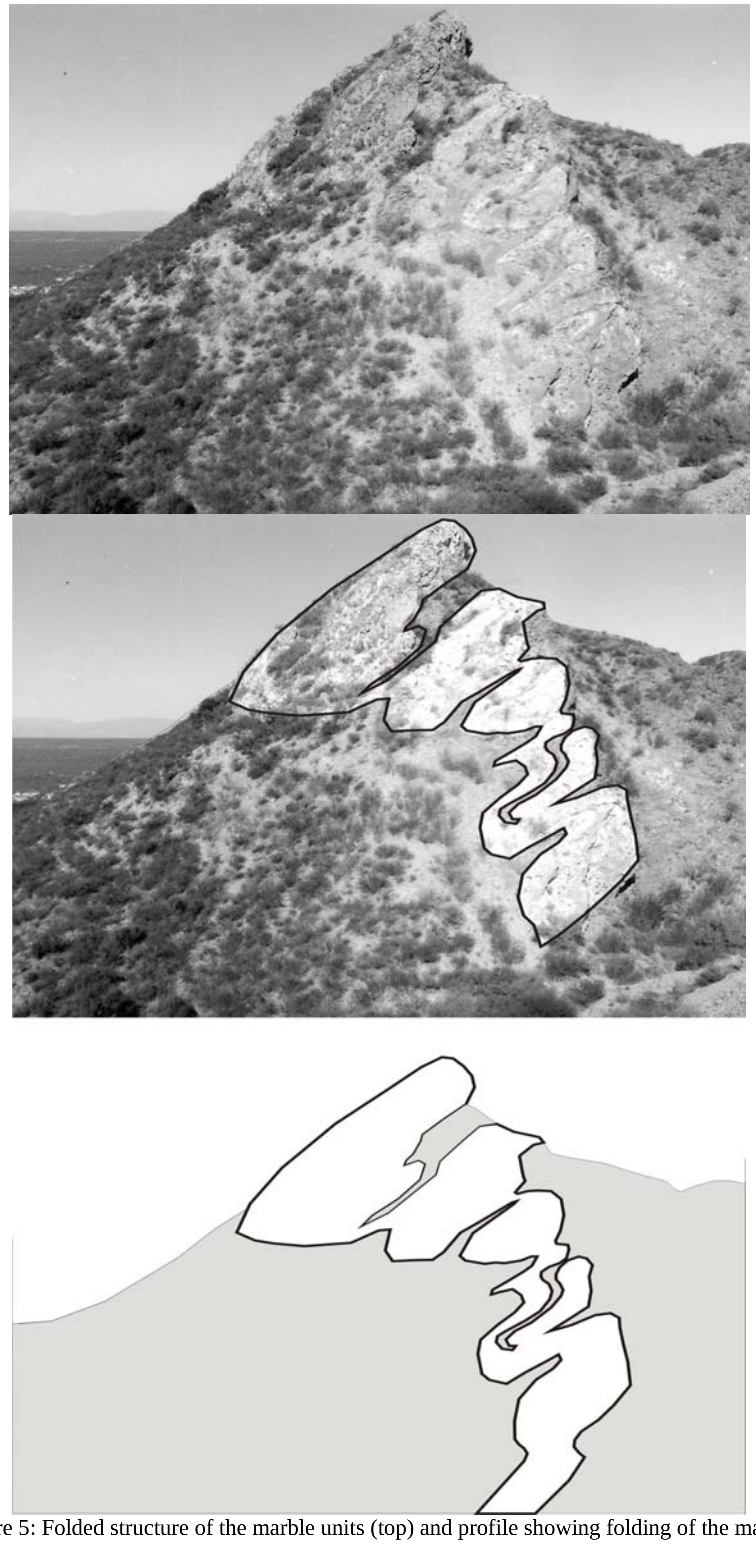

Figure 5: Folded structure of the marble units (top) and profile showing folding of the marble units with significant disharmonies (middle) and its representation (below)

The significant deformation observed makes stratigraphic correlation difficult, both from the geometric standpoint and considering the compositional variability of the subunits. Figure 6 illustrates the different structural characteristics encountered in each deposit, while Figure 7 shows a schematic of the interpretative model applied.

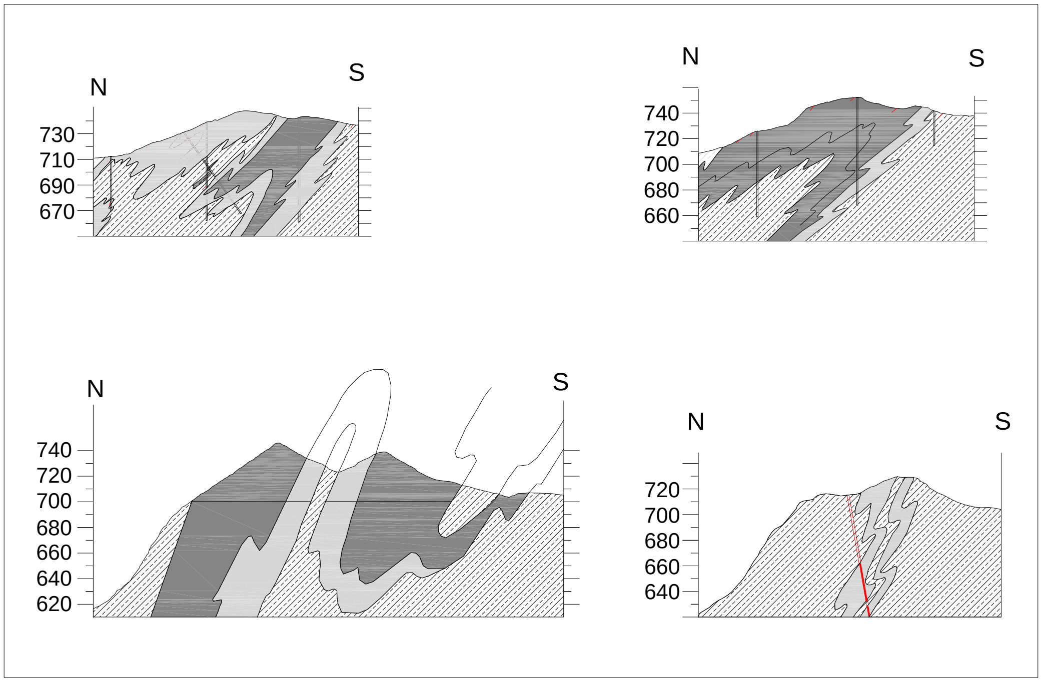

Figure 6: Schematic showing structural types in different deposits

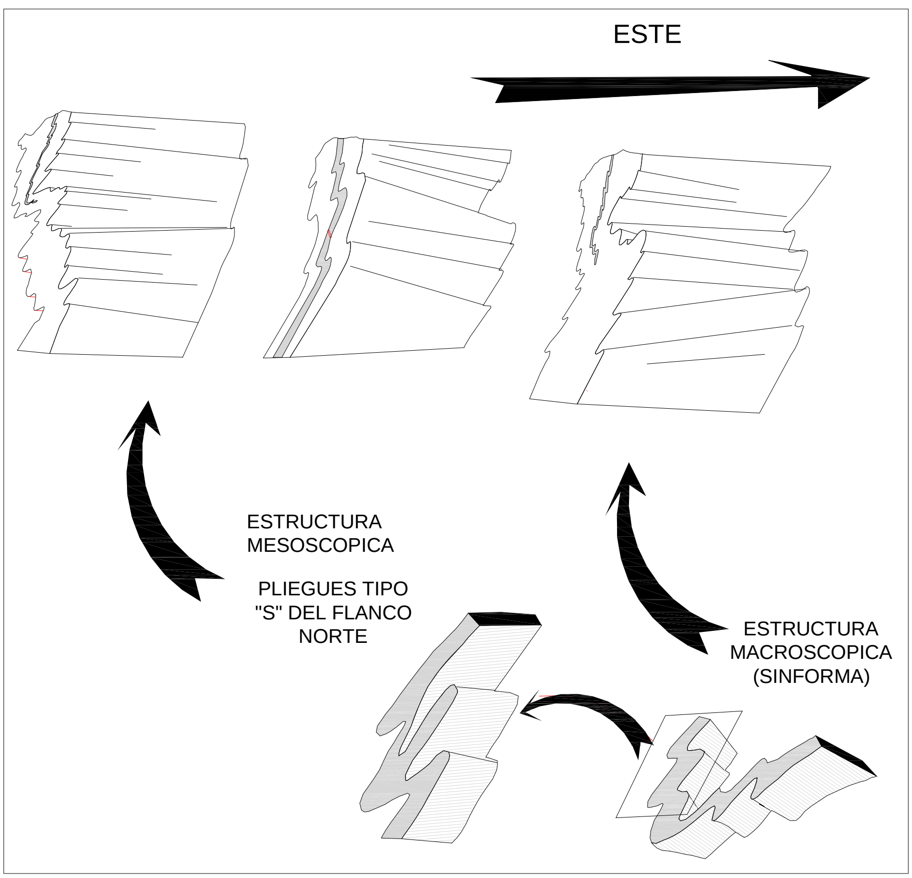

Figure 7: Structural model for marble sequences

CHEMICAL DATA AND MINERALOGY ANALYSIS

To characterise the deleterious elements that affect kiln performance, several assays are obtained which include SiO_2, Al_2O_3, Fe_2O_3, K_2O, Na_2O and SO_3. The assays were obtained from exploration drill hole core material as well as blast hole cuttings and samples taken from the mine faces. Also, the mineralogy was described using optical microscopy.

The main lithologies present in the three areas being currently mined (Cerros La Calera, Redondo, and Impuro) were described and its mineralogy characterised. The most significant impurities are quartz (SiO_2), with the chalcedony and opal phases being a minor content, muscovite ($KAl_2(Si_3Al)O_{10}(OH,F)_2$), and graphite (C).

The phyllosilicates are most easily identified and quantified under a microscope since these are muscovite-type micas. Graphite, on the other hand, is present on almost every unit defined, but is generally not abundant.

The different units are defined based on KST (Lime Standard), which quantifies the ratio of calcium oxide to hydraulic factors, and is defined according to Equation (1):

$$Kst = \frac{100 \times CaO}{2.8SiO_2 + 1.18Al_2O_3 + 0.65Fe_2O_3} \tag{1}$$

In the case of the Cerro Redondo, for example, 4 main units are defined and shown in Table 1; other deposits have slightly different definitions.

Table 1: Lithology units defined for Cerro Redondo

Lithologic Unit	*KST*	*Comments*
Marble 1	>90	High grade unit
Marble 2	65-90	Medium grade unit
Marble 3	50-65	Low grade unit
Schists	0-50	Barren

A key parameter that is of interest is the GS (degree of sulfation) is defined as:

$$GS = \frac{SO_3}{(K_2O + Na_2O) * factor} \tag{2}$$

Another parameter that is an indicator of kiln performance is MS (silicate modulus) which represent the weight ratio of silica to the sum of alumina and ferric oxide. MS varies between 1.9 and 3.2. Higher values imply lowering of the liquid phase in the kiln, with calcination and clinkering conditions worsening, which results in cements that require more time to harden and set. MS is defined as:

$$MS = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} \tag{3}$$

The flux modulus (MF) is the weight ratio of the minerals that result in the liquid phase:

$$MF = \frac{Fe2O3}{Al2O3} \tag{4}$$

There is up to 25% SO_3 in units for which the only sulphur minerals FeS_2 and $CuFeS_2$ (pyrite and chalcopyrite) do not exceed 2% of the total sulphur content. The alkali content, mostly as Na_2O, is high in relation to the rest of the mineralisation for the lithology units of interest.

GEOSTATISTICAL ANALYSIS AND MODELLING

Figure 8 shows the relative average content of SiO_2, SO_3, Na_2O, and K_2O for each of the three deposits being mined, showing their relative abundance and variability across deposits. In this Figure, all results from the exploration drill holes and the production information (blast holes) for the 2009 calendar year are included.

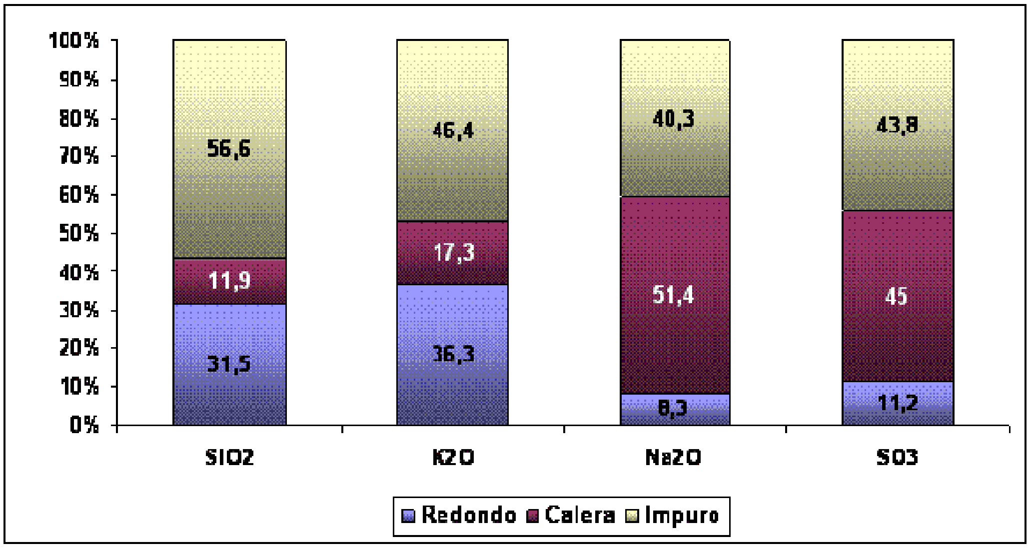

Figure 8: Average contents of silica, potassium oxide, Sodium oxide and sulphur trioxide for each deposit

The assays indicate that the greater S values (mostly as gypsum and pyrite) are found in Cerro La Calera deposit (high grade) and Cerro Impuro (low grade).

The higher silica concentrations are found in Cerro Impuro in the form of quartz (mostly), with minor chalcedony. The larger amounts of alkalis are found in Cerro Impuro and Cerro La Calera, as a mixture of muscovite mica and K-feldspar.

To date, modelling techniques have included applying the inverse distance squared method (IDS) to obtain estimated values for at least three key indicators (KST, MS, and GS), rather than the individual deleterious materials.

Block models are used to estimate grades from the exploration drill holes and production blast holes. Simple models have been the norm, although challenges in the processing and final product quality have necessitated a closer look at the long- and short-term modelling practices. Figure 9 shows an isometric view of the Cerro Impuro model, colour-coded by KST values and obtained by a direct estimation of KST values from drill holes and production blast holes into blocks.

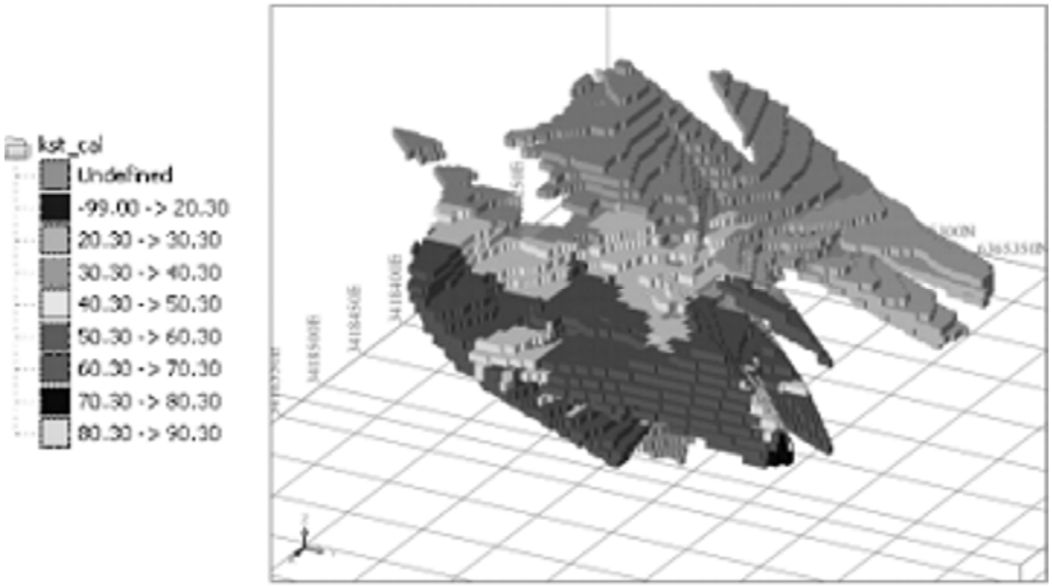

Figure 9: Isometric view of the KST model, Cerro Impuro

DISCUSSION AND CONCLUSIONS

There is the general misconception within the mining community that non-metallic deposits such as limestone or marble deposits are simple, easy to model and easy to mine.

The Sierra El Gigante marble deposits are located within a massif with high structural complexity, complicating its geologic modelling and the prediction of grades and key kiln performance indicators. In addition to the modelling difficulties, three deposits with very different geologic characteristics are being mined simultaneously.

The chemical assays are used to define a material mixture to be sent into the processing plant. The material is stockpiled prior to being fed to the plant. The stockpile content has to be accurately predicted, and thus the short-term information coming from mining faces and the blast hole assays are key. The practice of visually estimating a grade, even on a microscope, although helpful, is insufficient to predict the high level of variability of impurities in the stockpile.

Having recognised the complexity of the deposits and the intrinsic difficulties in accurately modelling its geology and predicting grades, the added value of improving the modelling methodology should become self evident.

The first significant improvement was recognising the need to incorporate the complicated structural geology to develop a good predictive model; although detailed descriptions of the geologic and structural characteristics of the deposits were available before (see for example, [2]), only in the last 2-3 years was a concentrated effort in geologic interpretation and modelling successfully implemented. This is summarised in this paper.

The next step in the path of continuous improvement is the search for a better estimation technique. There are two self-evident improvements: First, the estimated models should be upgraded from using Inverse Distance Squared estimation (IDS) to some form of linear or non-linear kriging estimator, depending on the distribution of the variables being estimated. Second, the blocks in the resource model should be populated with estimates of the individual elements or minerals. After the minerals' estimation is complete, calculate the key kiln performance indicators KST, GS and MS for each block according to Equations (1) through

(4). Since the kiln performance indicators result from ratios, direct block estimation using a linear estimation technique of these variables is theoretically incorrect.

From a pragmatic viewpoint, it is not yet understood whether the resulting KST, GS and MS estimates can still be acceptable approximations of the unknown true values. However, it would be safer to estimate the individual elements directly, which upscale linearly, and then combine them at the block level to provide the key indicators' block values. A worthwhile exercise would also be to compare the two approaches, since the differences provide insight into the short-scale spatial distribution of each variable.

Another series of techniques that are worth investigating is compositional data analysis, since the chemical and mineralogical assays can be considered to sum up to 100% of the rock. The potential advantage of this type of estimation is that the variables are estimated such that their relative proportions are maintained.

From the processing perspective, the variability of the deleterious elements can be more critical than the absolute content itself. This implies that additional future upgrades to the geostatistical analysis and modelling would have a greater focus on the prediction of the expected variability from the long- and short-term mine plans. The best method to accomplish this is an uncertainty and risk analysis based on geostatistical conditional simulations.

REFERENCES

Gardini, C., (1991), *Geología del Basamento de la sierra de El Gigante, Provincia de San Luis*., Unpublished Doctoral Thesis, Departamento de Geología, Universidad Nacional de San Luis., 249p [1].

Criado Roque, P.; Mombru, C. and Ramos, V., (1981), *Estructura e Interpretación tectónica*, in Yrigoyen, M. (Ed): "Geología y recursos naturales de la Provincia de San Luis: VIII Congreso Geológico Argentino", Relatorio: pp 155-192 [2].