

# MINERALOGICAL DEFORMATION OF THE BATHOLITH OF ANTIOQUIA

## DEFORMACIÓN MINERALÓGICA DEL BATOLITO ANTIOQUEÑO

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### Abstract

A systematic mapping of the Mineralogical Deformation (MD) of the batholith of Antioquia based on the petrography of a total of 211 rock samples is presented and discussed in detail. The microscopic observations of MD were previously performed by Thomas Feininger and Gerardo Botero 1982, which were based on the undulatory extinction of quartz, the presence of cataclasis, and the bending of biotite and plagioclase. The geostatistical analysis of the patterns of MD roughly differentiate two main deformational areas: the eastern area, with no evidence of MD minerals and the presence of undulatory extinction of quartz, and the western area dominated by the extinction wave quartz crystal bending of biotite and plagioclase. Spatial modeling of MD inferred a northern extension of the fault trace of Miraflores, which has been difficult to map in the northern sector due to lack of defined geomorphological expressions and which marks the deformation corridors mentioned above. Mineralogical Deformation (MD) must be taken into account when designing mortars and concrete mixtures in the selection of the aggregates. In this case, the facies located in the eastern part of Batholith of Antioquia have better conditions for construction of facilities, as they could ensure better structural quality of concretes and mortars.

**Keywords:** Batholith of Antioquia, construction materials, mineralogical deformation, geostatistics.

### Resumen

La cartografía sistematizada de la Deformación Mineralógica (MD) del Batolito Antioqueño con base en la petrografía de un total de 211 muestras de roca se presenta y discute en esta publicación. Las observaciones microscópicas de la MD fueron realizadas previamente por los profesores Thomas Feininger y Gerardo Botero en 1982, quienes se basaron en la extinción ondulatoria del cuarzo, la presencia de cataclasis y en el doblamiento de biotitas y plagioclasas. El análisis geo-estadístico de los patrones de MD permiten diferenciar a grandes rasgos dos zonas deformacionales: La primera de la zona oriental, con minerales sin evidencias de MD y la presencia de extinción ondulatoria de cuarzo. La segunda de la zona occidental, donde predomina la extinción ondulatoria de cuarzo, el doblamiento de cristales de biotita y de plagioclase. Del modelamiento espacial de la MD se infiere la prolongación norte de la traza de la falla Miraflores, la cual ha sido difícil de mapear en su sector norte debido a la carencia de expresiones geomorfológicas definidas y la cual marca los corredores de deformación arriba mencionados. La Deformación Mineralógica, (MD), es importante tenerla en cuenta a la

hora de diseñar morteros y hormigones como fuente de áridos. En este caso, las facies localizadas en el sector oriental del Batolito Antioqueño presentan mejores condiciones para la construcción ya que podrían garantizar morteros y hormigones de calidad superior.

**Palabras claves:** Batolito Antioqueño, Deformación Mineralógica, Geoestadística, Materiales de construcción.

## INTRODUCTION

The Batholith of Antioquia (BA), is a body of igneous nature located on the northern side of the Central Cordillera of Colombia, which outcrops over an area of approximately 7800 km<sup>2</sup> excluding satellite bodies separated from the main body of metamorphic rocks. Aspects related to the geological environment, contacts, inclusions, thermal aureoles, dikes, consistency, texture and mineralogy have been reported previously by Feininger and Botero (1982). On the occasion of the Third Seminar "Gerardo Arango Botero" on the geology of the Central Cordillera of Colombia, the geostatistical deformation analysis of the BA was developed with the main objective of presenting the major mineralogical findings in this paper.

## GEOLOGICAL CONDITIONS

Two hypotheses have been considered to explain the origin of the BA: magma injection (Botero 1963; Feininger *et al.* 1972; Feininger & Botero 1982; González 1997), or by of treplacement preexisting rocks in-situ (Radelli, 1965, a, b, c; 1967). Field and laboratory criteria expressed in different works of the regional geology are more compatible with a magmatic origin, among these criteria is worth noting the following:

**Contacts:** None of the outcrops located and described near the BA there is gradation between the rock of the batholith and the surrounding rock. Sharp contacts were produced by the injection of magma. All contacts are discordant and the batholith rocks cut the foliation and compositional layering of the rock. The spatial relationships suggest that contact with the host rocks is also discordant.

**Inclusions:** Surrounding rock inclusions in the BA have an internal structure rotated relative to neighboring inclusions and truncated by the rock of the batholith.

**Contact Aureole:** The contact aureole of the BA has high-temperature metamorphic assemblages which are not in equilibrium with those in the host rocks.

**Dikes:** The dikes in the host rock of the BA are discordant and have sharp contacts. Where calcareous rocks

have been cut, they suffer desilicification forming rocks rich in calcium silicates caused by the reaction with the calcareous rocks.

**Uniformity:** The extraordinary compositional uniformity can be explained most easily by crystallization from a homogeneous magma.

**Texture:** The hypidiomorphic granular texture that characterizes the normal facies of the BA is consistent and can be explained by crystallization from a melt mass which follows an order determined by a decreasing temperature and to an increasing content the silica in the mineral facies. No evidences of an incomplete replacement of metamorphic rocks or any other rocks have been found.

**Zoned plagioclases:** They are consistent with equilibrium crystallization of a magma silicon and correspond to a series of continuous reaction of Bowen obtained experimentally. Clinopyroxene cores in hornblende and the fact that the biotite is less euhedral than the hornblende reproduce the order of crystallization of materials or mixtures of fused silica and constitute the series of discontinuous reaction.

The sharp and discordant contacts of the BA and the absence of foliation are characteristic of batholiths intruded in epizone (Buddington, 1959).

## MINEROLOGY

Mineralogically speaking the normal facie of the BA consists of quartz, feldspar, hornblende and biotite varying relatively between close values, such as alteration minerals, chlorite, epidote and calcite. The quartz is presented in dispersed anhedral crystals and as a interstitial filler between plagioclase, showing occasionally undulatory extinction. Not twinned feldspar occurs as anhedral crystals mainly in optical continuity, interstitial between euhedral crystals of plagioclase, hornblende and biotite and microperitita which are developed in some samples.

Plagioclase, mainly andesine, which constitutes about half of the rock, is present in the form of subhedral to euhedral crystals, well twinned like accoralbite, albite-Car-

Isbad and Pericline: It is common the zoning (normal to oscillatory), although in the same sample may appear unzoned crystals (containing small inclusions of hornblende and clinopyroxene), and shear zones (which can be replaced by potassium feldspar). The Hornblende occurs mainly in euhedral to subhedral crystals of prismatic habit with well-defined pleochroism with X= yellowish green, Y= green, Z= brownish green with occasional changes in color, probably due to a change in relations Fe/Ti and FeO/Fe<sub>2</sub>O<sub>3</sub>; occasionally, presenting uncolored nuclei of clinopyroxene and opaque fine-granular associate.

Biotite occurs in euhedral to subhedral sheets in most free samples of deformation, strongly pleochroic with X = pale yellow; Y = Z= brown to reddish brown, and generally showing evidence of chloritization with sphene segregation which is accumulated as microgranular aggregates along the cleavage planes. Common inclusions are those of zircon with strong pleochroic halo. Accessory minerals dominant in this facies are apatite, magnetite and zircon, and to a lesser extent sphene, epidote, calcite, allanite, and prehnite of diuretic origin. It is common in rocks of these facies the presence of lenticular to ovoid forms of fine grain, solid, dark gray with megacrysts of plagioclase or hornblende contrasting by its color and composition with the enclosing rock. These forms of batholith having the same composition of the normal rock except for quartz and the mafic enrichment are known as “GABARROS” in spanish (Botero 1963).

## DATABASE

The database used for this work comes from the random sampling of a grid shown in Figure 1, and presented in

Table 3 of the petrological study of the Batholith of Antioquia - Colombia, carried out by Feininger and Botero (1982). The BA was mapped at scales ranging from 1:25,000 to 1:100,000 by geologists from INGEOMINAS, as well as students and professors of the National School of Mines at Medellin between 1959 and 1968. The work was initiated by Professor Gerardo Arango Botero, and his students around the city of Medellin, Antioquia, Colombia. Although the database includes more than 1000 field samples, only 207 of these samples were selected representing the normal facies of the BA.

Samples were analyzed using standard microscopic techniques of polarized light. Feininger and Botero (1982), established a quantitative measure of the deformation of the minerals establishing a scale from zero to four, as follows: Zero= when there was no evidence of deformation of minerals; 1= undulatory extinction of quartz, 2= biotite bending; 3= bending of plagioclase; and 4= cataclasis. The histogram shown in figure 3, indicates that 79% of the samples reported some mineralogical deformation, which may be the product of crustal deformation or attributable to post-intrusive faultings of environments primarily distensional.

## SPACIAL DEFORMATION OF STRUCTURE

The beginning of any geostatistical study, requires a structural analysis of the variable under study and this, is done through the development of the variogram. The methodology for this type of analysis has been presented extensively by Journel & Huijbregts (1978), Isaaks & Srivastava (1989), and Chiles & Dolphins (1999).

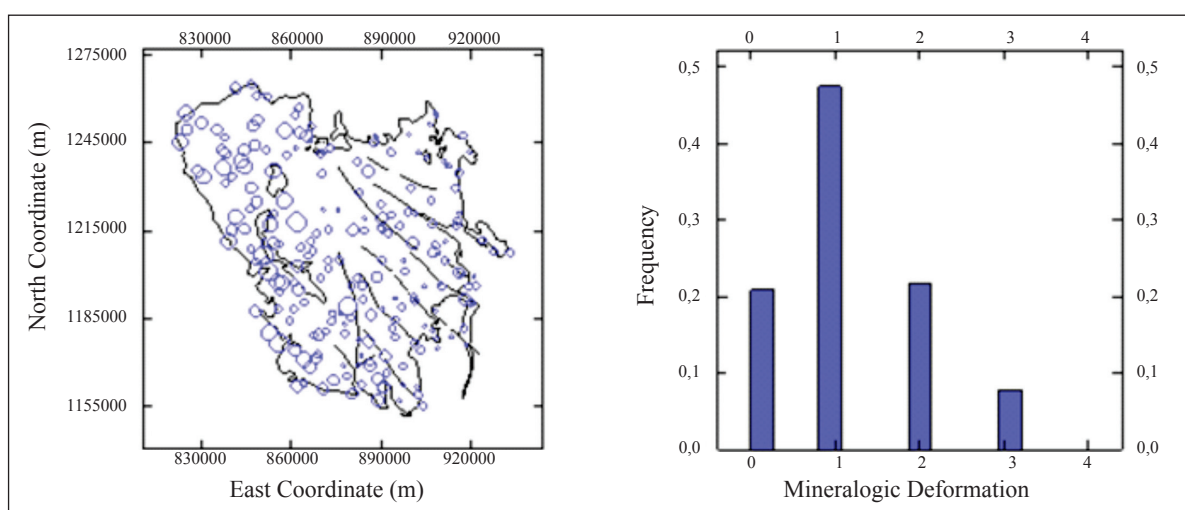


Figure 1. A. Random sampling grid. B. Histogram of mineral deformation

Figure 2A, shows the semi-variograms representing experimental and theoretical deformation developed for the mineralogical variable of the BA including the number of partners representing each point. A omni-directional semi-variogram was chosen because it was not detected any presence of significant anisotropies, so a representative structure was obtained of a spherical model  $\gamma(h) = Esf(2.7, 0.62)$  with a range of influence of 2.7 km with a sill of 0.62 (i.e., with a variance which represents 70% of the statistical variance or variance "a priori"). The validity of this spatial model was verified through a cross-validation technique, which consists of estimating each of the experimental data based on a variographic model and the punctual method of Ordinary Kriging. Once the new estimates are calculated, a scatter plot of estimated data ( $z^*$ ) against the standardized error ( $(z-z^*)/s$ ) can be obtained.

Figure 2B which corresponds to the scatter plot between actual and estimated values using these mivariogram modeling (See figure 2A), indicates that of the 207 samples considered in this study, only 4 (2% of total) are for outside the conditions of spatial variability considered; therefore, the selected theoretical model can be considered representative for the mapping of the MD (Mineralogical Deformation) of the Batholithic of Antioquia. Table 1, lists

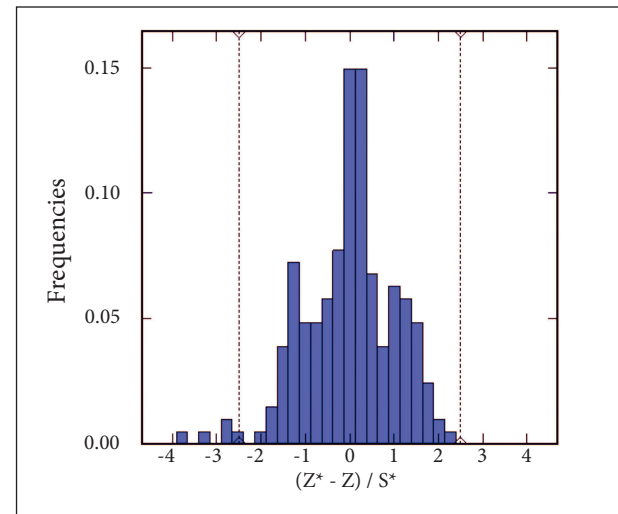
**Table 1.** Statistics

Statistics based on 203 data points	Average	Variance
Error	0.04551	0.5429
Standarized Error	0.0560	0.8599

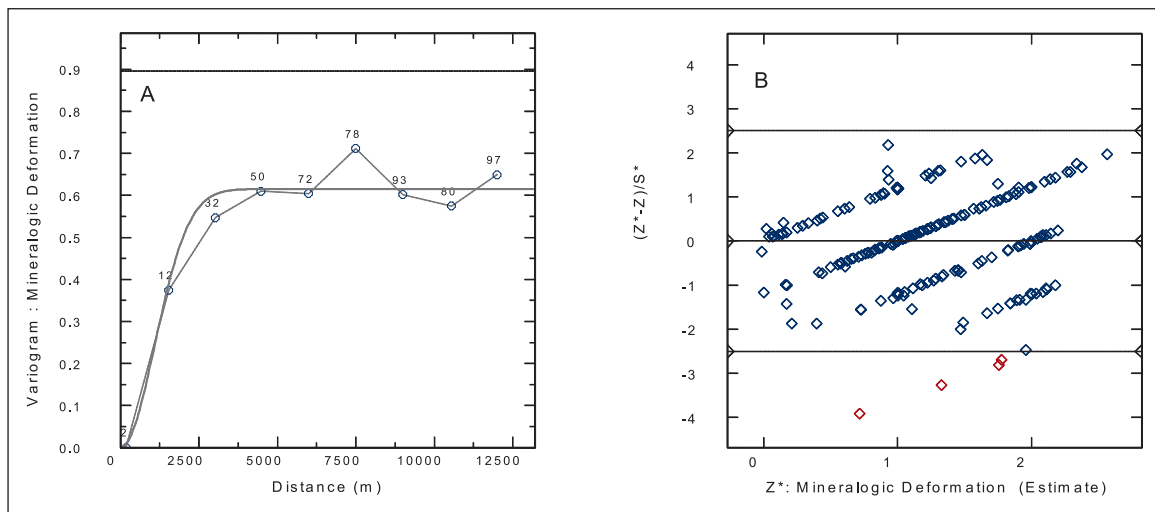
the statistics based on the errors of the 203 selected data. Figure 3, shows that the distribution of errors can be considered Gaussian.

Note that a structural analysis (i.e., variography), has been prepared taking into account the geological fault system affecting the BA in the central and south eastern ends.

Considering the fault system is important from the point of view of geostatistics, as the cartographic maps, will help to identify the importance of faulting on the status of mineralogical deformation. Also note that the weights have to meet the sum indicated above, since in the particular case when all values are equal to a constant, the estimated value may be equal to that constant.



**Figure 3.** Standardized error histogram  $[(z-z^*)/s^*]$

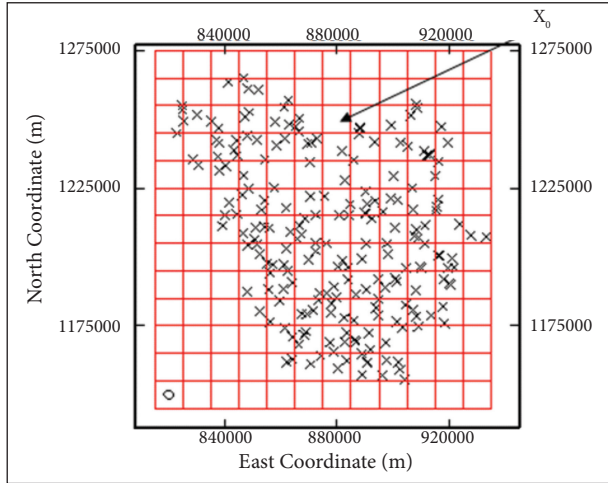


**Figure 2. A.** Semi-variogram for the mineralogical deformation variable. **B.** Dispersion estimated values ( $z^*$ )-versus-Standardized Error  $[(z-z^*)/s^*]$

## GEOSTATISTICAL ESTIMATION OF STRUCTURE

Geostatistics, has been recently used by the first author on 2012. The geostatistical estimation method used for modeling the spatial variation of the degree of mineralogical deformation, is the Ordinary Kriging of blocks. This method consists of estimating a value  $x_0$  (Figure 4), using the known values of each point of the neighborhood making a sampling  $x_\alpha$  and by combining them linearly with the Kriging weights  $\lambda_\alpha$  as indicated by the following expression:

$$Z_{KO}^*(x_0) = \sum_{\alpha=1}^n \lambda_\alpha Z(x_\alpha)$$



**Figure 4.** Control samples randomly spaced and location of the sample of interest ( $x_0$ )

It is assumed that the data are part of an embodiment of an intrinsic random function  $Z(x)$  with a variogram  $\gamma(h)$ . Any skewness is avoided ensuring that the sum of the weights is equal to unity.

$$E[Z^*(x_0) - Z(x_0)] = E\left[\sum_{\alpha=1}^n \lambda_\alpha Z(x_\alpha) - Z(x_0) \cdot \sum_{\alpha=1}^n \lambda_\alpha\right] \quad (1)$$

$$\sum_{\alpha=1}^n \lambda_\alpha E[Z(x_\alpha) - Z(x_0)] = 0 \quad (2)$$

Because the expectations of the increments are zero therefore, the estimated variance  $\sigma_E^2 = \text{var}[Z^*(x_0) - Z(x_0)]$  becomes equal to the variance of the lineal combination expressed by equation (3):

$$E[Z^*(x_0) - Z(x_0)]^2 = \sum_{\alpha=1}^n \lambda_\alpha Z(x_\alpha) - 1 \cdot Z(x_0) = \sum_{\alpha=1}^n \lambda_\alpha Z(x_\alpha) \quad (3)$$

Since the sum of the weights  $\lambda_\alpha$  equal to 1

$$\sum_{\alpha=1}^n \lambda_\alpha = 1 \quad (4)$$

This last condition implies that the use of the variogram is correct in calculating the estimated error, the variance is estimated as follows:

$$\sigma_E^2 = E[(Z^*(x_0) - Z(x_0))^2] = -\gamma(x_0 - x_0) - \sum_{\alpha=1}^n \sum_{\beta=1}^n \lambda_\alpha \lambda_\beta \gamma(x_\alpha - x_\beta) + 2 \sum_{\alpha=1}^n \lambda_\alpha \gamma(x_\alpha - x_0) \quad (5)$$

By minimizing the variance, the Ordinary Kriging (OK) is obtained.

$$\begin{pmatrix} \gamma(x_1 - x_1) & \cdots & \gamma(x_1 - x_n) & 1 \\ \vdots & \ddots & \vdots & \vdots \\ \gamma(x_n - x_1) & \cdots & \gamma(x_n - x_n) & 1 \\ 1 & \cdots & 1 & 0 \end{pmatrix} \begin{pmatrix} \lambda_1 \\ \vdots \\ \lambda_n \\ \mu \end{pmatrix} = \begin{pmatrix} \gamma(x_1 - x_0) \\ \vdots \\ \gamma(x_n - x_0) \\ 1 \end{pmatrix} \quad (6)$$

Where:  $\lambda_\alpha$  = weights assigned to the data values; and  $\mu$  = Lagrangian parameter.

The left side of the system describes the similarity between each datum and the estimated point  $x_0$ . Using matrix multiplication, the Ordinary Kriging system, can be rewritten in following the form:

$$\begin{cases} \sum_{\beta=1}^n \lambda_\beta \gamma(x_\alpha - x_\beta) + \mu \\ \sum_{\beta=1}^n \lambda_\beta = 1 \end{cases} \quad \text{for } \forall \alpha = 1, \dots, n \quad (7)$$

The variance of the estimation for the Ordinary Kriging can be obtained using equation (8)

$$\sigma_{OK}^2 = \mu - \gamma(x_0 - x_0) + \sum_{\alpha=1}^n \lambda_\alpha \gamma(x_\alpha - x_0) \quad (8)$$

The Ordinary Kriging is an exact interpolator in the sense that if  $x_0$  is identical with the location of the data then the estimated value is identical to the data value at that point.

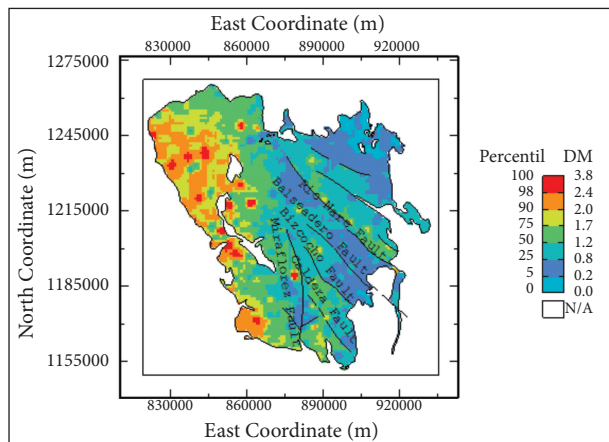
$$Z^*(x_0) = Z(x_\alpha) \quad \text{when } x_0 = x_\alpha \quad (9)$$

This can be easily seen: when  $x_0$  is an estimation point, the right side of the Ordinary Kriging system is equal to a left-hand column of the matrix. The solution to the system is obtained through a weight vector with a weight  $\lambda$  for each column equal to one and all other weights (including  $\mu$ ) equal to zero. As the left side of the matrix is non-singular, the solution is unique.



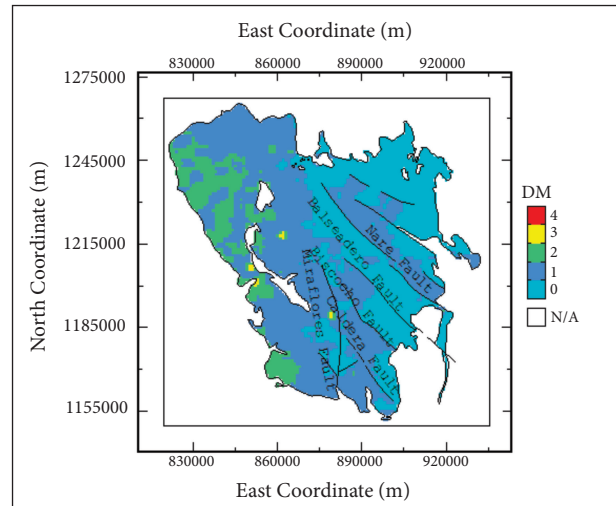
## RESULTS

A total of 6653 blocks of MD were estimated using a grid of approximately 1 km<sup>2</sup>. These blocks have been represented using 7-color categories based on statistics from the percentiles 5, 25, 50, 75 90 and 98 on a map shown in figure 5. The 50% percentile equals the median (1.2) and since the data set estimates are normally distributed (kurtosis= 2.8, skewness= 2.2, mean= 1.2), the confidence level of this data is in the range  $z \pm 2\delta_{ok}$  (where  $\delta_{ok}$  = Ordinary Kriging standard deviation), thus the outliers of the MD (on average) are above  $1.2 \pm 2*0.1$ .



**Figure 5.** Mapping of mineralogical deformation of Batholith of Antioquia (based on the application of Ordinary Kriging of blocks considering the category of classes established for microscopic observation and the results).

This means that a numerical value of 1.70 MD can be considered as a threshold. From the statistical point of view, this threshold helped to identify that the patterns of maximum MD is associated mainly to the western part, while the eastern end the MD is strongly influenced by traces of geological faulting mapped by Feininger & Botero (1982). The map shown in figure 6, was developed considering the category of classes established by microscopic observation of the samples, allowing to clearly visualize that the Miraflores fault NS-NW orientation is a structural control on the categorization of the MD of BA. This contains a predominantly undulatory extinction of quartz and with the presence of bended biotite in the west and with no deformation or undulatory extinction of quartz to the east of that structure. This division of the BA of two deformational blocks allows to reach the conclusion that the fault system Cauca-Romeral, which outcrops to the west, has had more influence deformational on the batholiths that the fault system located east of Palestine.



**Figure 6.** Mapping of mineralogical deformation of Batholith of Antioquia (resulting from the application of Ordinary Kriging of blocks). Note that: 0= when there was no evidence of deformation of minerals; 1= undulatory extinction of quartz; 2= biotite bending; 3= bending of plagioclase; and 4=cataclasis

## CONCLUSIONS

Based on the geostatistical analysis of the patterns of MD of the Batholithic of Antioquia, two zones can be differentiated:

- The Eastern Zone, with no evidence of MD minerals and the presence of undulatory extinction of quartz.
- The Western Zone, dominated by an undulatory extinction of quartz, kinked biotite and plagioclase crystals.
- The spatial modeling of Mineralogical Deformation, inferred the northern extension of the fault trace Miraflores, which has been difficult to map in the northern sector due to lack of geomorphological expressions defined and which marks the deformation corridors mentioned above.

The mineralogical deformation analysis of rock materials of the BA presented in this paper is of particular importance for the infrastructure Colombia and its construction industry in proper design of mixtures for mortars and concretes.

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