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EVALUATION OF THE RESERVE OF A GRANITE DEPOSIT BY FUZZY KRIGING

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ABSTRACT

In the present study, we describe a method for estimating the reserve in an ornamental granite deposit. The method is adapted to the existing optimised mining method and provides a more realistic estimate of commercial quality than conventional methods. Using a batholith geology-mining map, a description of fracturing in the mining area, and underground information provided by continuous-core boreholes, an estimate of reserves was made that featured the following innovations: 1) the use of fuzzy set theory to assign qualities to each block, and 2) the inclusion of fracture anisotropy at the deposit level in the fuzzy mathematical formulation. These innovations enabled quality distributions in the rock mass to be assessed more realistic, by reducing the estimation error caused by assigning a single quality to the primary block and by improving the estimate of the distribution of commercial qualities defined by fracturing. This method produced a satisfactory estimate of the commercial qualities of one of the world's most important granite deposits (in

northwest Spain). The results have been stored in a database—linked to a graphic representation of the blocks (similar to a geographical information system)—which, by providing automatic access to information in regard to the location of the best quality commercial blocks, ultimately optimises mining planning.

KEYWORDS: granite; reserve estimation; mining exploitation; fuzzy kriging; GIS

1. INTRODUCTION

Granite, as a natural material with excellent construction properties, is a geological resource of increasing economic importance. The granite extraction sector in Spain is currently experiencing a boom. A main production area in Spain is Galicia, where 45% of the lithologic units is formed by granite.

This type of rock is exploited in outcrops of plutons. Estimating reserves is not overly complex, although the task must be carried out rigorously and exhaustively. It requires the compilation of topographical and geological maps and a characterisation of the structural and textural parameters of the deposit (at various scales) that define rock quality and that condition the exploitation methods (Muñoz de la Nava et al., 1989). The quality of granite as ornamental stone depends on various factors such as grain size, colour, the presence of black-knot flow structures, and weathering (Taboada et al., 1999). The exploitability of granite, on the other hand, is determined by structural characteristics such us mainly orientation, family, extension, persistence, and continuity and discontinuity densities, irrespective of whether the fractures or joints are of primary or secondary origin (ISRM, 1978; Muñoz de la Nava et al., 1989; Toyos et al., 1994). The natural rock mass discontinuity pattern determines the deposit ratio, in that it determines the minimum block size that can be extracted and the approach to extraction.

Good quality granite that forms outcrops in large plutons is likely to be mined over the long term, and reserve estimation in this case should take into account long-term planning and sustainability over time—not only from a market and business point-of-view (especially if there are several licenses involved) but also from the environmental perspective. To date, reserve estimation methods have not responded to this need.

One of the world's most important granite deposits— the Rosa Porriño batholith situated in the province of Pontevedra (northwest Spain)— is the material of the present study. The importance of this deposit, which supplies ornamental stone of high technical and aesthetic quality, lies both in the size of the pluton exploited (the licensed mining area is 6.8 km^2) and the number of companies involved in exploitation (39 mining concessions have been granted). Due to the volumes of the batholith and the textural homogeneity of the rock, this deposit is expected to be profitable for a considerable period of time. Its pink biotitic granite is, in general, highly uniform in terms of tone, grain size and finishing technique behaviour. The rock is extracted using the diamond-wire cutting method—which conditions the size of the primary block (10mx10mx10m, i.e., 1000m^3)—and is subsequently cut to size to obtain commercial-sized slabs using wire, drilling and contour blasting.

We describe an innovative method for estimating ornamental stone reserves, especially designed for large batholiths like the Rosa Porriño deposit. This method is adjusted to the true size of the extracted 1000 m^3 blocks (primary blocks). It takes account of the fact that there may be different qualities within a block and that the definition of qualities is subject to uncertainty. The size of the blocks to be obtained from a quarry extraction pit is an essential factor in the profitability of a mining operation, and so it is crucial to characterize size accurately before cutting. Undoubtedly, knowing the quality of each block prior to cutting means that a more realistic economic forecast can be made, based on mine planning that takes into account market needs and more rational long-term exploitation.

Our estimation method is based on a traditional survey method that uses, as a starting point, batholiths geological-mining maps, a description of fracturing at mining areas fronts, and vertical information provided by continuous-core boreholes. Fracturing is the parameter that defines the commercial quality of the granite, and four qualities that depend on the intensity of fracturing were considered: top quality rock and secondary quality rock (for the ornamental rock market), rock for transverse masonry, and rock for construction aggregates.

We included an operational focus in the conventional methodology that yielded a more objective and realistic estimation of the reserve, as follows:

1) Account was taken of the exploitation method, which is optimised for the extraction of 1000 m^3 blocks, in the reserve estimation process. The deposit was divided into cells of the same size and fuzzy kriging (Diamond, 1989) was used to estimate the reserves for the whole exploitable zone from the cells for which quality information was available.

2) Fuzzy set theory was used to assign qualities to blocks. Integrating geostatistical concept with fuzzy set theory is a quite novel direction and the application of fuzzy modeling in reserve estimation is very limited. Nefeslioglu, Gokceoglu and Sonmez

(2006) obtain some statistical and fuzzy models for predicting weighted joint density to evaluate block size. Luo and Dimitrakopoulos (2003) and Bardossy, Szabo and Varga (2003) have applied the fuzzy set theory in reserve estimation and mathematically evaluated the spatial continuity of ore bodies by fuzzy sets. Recently, Tutmez, Tercan and Kaymak (2007) have carried out a study that tries to combine fuzzy algorithms and spatial variability in reserve estimation. Fuzzy logic has been successfully applied as a quality evaluation tool for other resources—such as kaolin (Taboada et al., 2006b) and slate (Taboada et al., 2006a)—in which the boundaries between different qualities (defined using a set of physical, chemical and aesthetic parameters) are not clearly defined. In the case described here, the application of fuzzy logic to the estimation of granite reserves seemed particularly appropriate. Fracturing — the parameter that conditions deposit quality — varies throughout the length of a deposit, which would indicate the suitability of a grading system for the different commercial qualities that might be found in any given 1000 m^3 block. A fuzzy triangular function was applied to the block quality definitions that reflected the gradual changes in block quality resulting from fracturing (which ultimately indicates commercial quality). This approach also reduced error in estimating the overall exploitability of a deposit in terms of each quality band, as no single quality was attributed to a primary block.

3) Deposit-level fracture anisotropy data was incorporated in the fuzzy kriging estimate. Fracturing of the granite shows an anisotropic behaviour, in other words the property of being directionally dependent. This has to be taken into account in order to calculate the kriging estimations correctly. Working with anisotropic data is

the usual situation when estimating by kriging methods with hard data, or crisp data as is referred by some authors (Bastante et al., 2005) (Chambers, Yarus and Hird 2000a, 2000b) and Demico (2004) are previous papers where anisotropy and fuzzy information are taken into account but, as far as we know, this is the first research where the kriging algorithm is modified in order to model anisotropy together with fuzzy information.

2. MATERIALS AND METHODS

2.1 Description of the deposit

The reserves that were estimated using our method are located in the Rosa Porriño Massif, in the province of Pontevedra in northwest Spain (Figure 1). This late- to post-kinematic batholith is situated in one of the Hercynian sectors in the northwestern Iberian Peninsula (the Iberian-Armorican arc). It has outcrops some 25 km in length, running N-S in the border area between the Spanish provinces of Ourense and Pontevedra and the north of Portugal. The main plutonic body has discordant intrusive contacts with the adjacent materials (two-mica granites and paragneisses), over which contact metamorphism has developed (I.G.M.E., 1981). It is also discordant with the regional Hercynian structures (schistosity and folding of the meta-sediments and foliation of the two-mica granites). From a lithological perspective the massif is composed of several granite facies; the most interesting—from the ornamental rock perspective—is the equigranular Rosa Porriño facies. This biotitic granite, which has a grain size that ranges from thick to very thick (4-15 mm), is very rich in potassic feldspar (more so than in plagioclase).

This granite is observed as homogeneous at the outcrop scale; it has few enclaves, and those that exist are typically granodiorite or quartzodiorite enclaves, measurable in decimetre or centimetre terms. Phylonian manifestations correspond to a typical granite landscape conditioned by the fracture network and characterized by regoliths alternating with well-rounded granite blocks.

The project was implemented in one of the largest mining concessions (6.8 km^2), of which 2 km^2 is currently being exploited. This surface area is distributed over altitudes ranging between 15 and 285 metres. The primary block size of 1000m^3 is conditioned by the mining method: diamond wire is used to cut out and isolate the primary block, which is subsequently cut up further (via perforation and blasting) into slabs that are turned for further dimensioning.

The research domain is defined by terrain classified as agricultural to the north and south, by an industrial estate (where a number of granite plants are located) at the western boundary, and at the eastern boundary, by an outcrop from the porphyric pink granite facies (Rosa Porriño granite), representing a granite variety with a different ornamental value to the equigranular facies (Figure 1). The vertical limit (Z axis) is marked by the outcrop surface area (upper limit) and borehole depth (lower limit).

2.2 Reserve evaluation

The method applied to estimate the reserves of the granite deposit consisted of two phases such as documentation and field data-collection, and fuzzy kriging application.

2.2.1 Documentation and field data-collection

For the documentation and field data-collection phase, the mining parameter of interest for defining rock quality (and therefore for estimating reserves) was the level of mass fracturing, given that textural features—such as grain heterogeneity and the presence of phenocrystals, weathering bands or black knots—have little bearing on the quality of a granite as homogeneous as that of the studied deposit. On the basis of this premise, fractures in the exploitable zone were assessed on the basis of:

1) A 1:3.500-scaled map of the deposit featuring topographical, geological and fracturing details.

2) A description of seven continuous-core boreholes (from a total drilling length of 304.35 m) to complement vertical information on the deposit for parts that are as yet inaccessible.

3) A description of fractures for profiles corresponding to the current quarrying zones.

The fractures were characterised by spatially analyzing the direction, dip, spacing, opening, filling and roughness for a total of 312 diaclases and 41 fault segments. For the purposes of this study, we distinguished between two fracture domains: fractures corresponding to faults or diaclases with significant continuity and spacing (> 2 m), which typically form the basis for delimiting blocks; and fracture bands characterised by high fracture density (spacing < 2 m and typically decimetric), which generally indicate poorer quality granite. This information was input to a stereographic equiareal projection—which represented the families of poles—with the aim being to detect areas where fracture bands were more representative. Areas where fractures had the greatest influence on rock quality were thus identified, as also preferred fracture orientation in the rock mass (i.e., anisotropy, which was a parameter taken into particular account in the kriging application).

A network of sampling blocks was defined, on the basis of which kriging was used to interpolate data for the entire deposit. The sampling unit was the primary block measuring $1000m^3$. Blocks which outcropped or which were vertically or horizontally cut in the deposit (i.e., for which data was available in two dimensions) represented the data input cells. Fracturing — as the parameter that determines the extraction of one or more products of different commercial values — was translated in terms of different commercial quality grades. This definition of more than one quality for a block represented one of the innovative aspects of our reserve evaluation method, and consequently, for each input cell, the following quality classes were defined:

a) Top grade rock (optimal ornamental quality): rock that can be extracted in sufficiently large volumes to obtain gangsaw-sized slabs, i.e., rock with few fissures capable of yielding blocks of 6-12 m^3.

b) Secondary grade rock (adequate ornamental quality): rock yielding blocks of less than 6 m^3 but still valid for the gangsaw, with discontinuity spacing of > 2 meters.

c) Tertiary grade rock (construction or transverse masonry quality): fractured rock that will yield semiblocks (blocks of less than 4 m^3), with discontinuity spacing of < 2 meters.

d) Low grade rock (construction aggregate quality): highly fractured rock with a market value only as crushed aggregate.

These qualities are referred to below on a scale of 1 (top grade rock) to 4 (low grade rock).

2.2.2 Fuzzy kriging application

Basic fuzzy set theory tools

Quality grading of a specific block is difficult to implement with strict precision or accuracy, which means that a certain degree of uncertainty is associated with the task. This uncertainty may arise for reasons such as the fact that it is difficult to accurately characterise an entire block in terms of percentages for each quality class (since only partial observations can be made of some of its faces), or because the quality classes as defined by the experts are, in themselves, subject to a certain degree of uncertainty.

Fuzzy set theory, which was first described by Zadeh (1965), is particularly indicated for handling the kind of imprecise information dealt with in our problem. A fuzzy set, A, defined for the set of real numbers x, is a set or ordered pairs:

$$A = \{[x, \mu(x)]\}$$

where $\mu(x)$ is the membership function for x in A that takes values in the interval $[0,1]$. Values close to 0 indicate a low grade of membership, whereas values close to 1 indicate a high grade of membership. As a particular case, the fuzzy number is a fuzzy set of the set of real numbers with a convex membership function such that $\mu(x) = 1$ is satisfied for at least one point.

The triangular function applied to primary block quality assessment.

Another innovation in our approach was to use fuzzy information in conventional kriging. Fuzzy set theory and in particular fuzzy number theory adapts perfectly to our model for assigning quality classes to a primary block of 1000m^3 according to the level of fracturing. Fracturing typically varies throughout a block, both qualitatively and quantitatively, in terms of intensity, spacing, direction, etc. If a block is assigned a single grade that fails to reflect likely variations in rock quality, then economic estimates as to yield may turn out to be erroneous and ultimately costly.

Furthermore, since qualitative and quantitative changes in block fracturing—and consequently, in ultimate commercial quality—occur progressively throughout a block, it is both conceptually incorrect and physically impossible to establish clear cut-off boundaries between quality classes. In other words, there are fuzzy boundary areas between quality classes. This gradual change in fracturing implies a degree of uncertainty in the spatial (and percentage) definition of qualities. This is also a potential source of estimation error, although the resulting error will be smaller than the error resulting from assuming a single quality class for such a large block.

Using a procedure based on fuzzy set theory, we employed a triangular function to the task of assigning quality classes to both the model input data and the results. Fuzzy numbers and triangular membership functions (much used in fuzzy set theory) were used, mainly because of the simplicity of the approach and the fact that it could easily be computationally implemented, and also because it is sufficiently flexible to be able to adequately reflect the information available.

The base of the triangle for each block with a known quality value was constructed from an X axis that numerically represented the established commercial quality classes. For a primary block representing just a single commercial quality (Figure 2 (a)), the triangle was constructed by fixing the vertex (with a value of 1 on the Y axis) to the point corresponding to the prolongation of the quality value. The triangle base had a dimension of 0.3 units on each side of the corresponding quality. For a block with two quality classes (Figure 2 (b)), the rates for the two qualities (expressed as decimals) were drawn along the Y axis, and the vertex of the triangle (with a value of 1 on the Y axis) was fixed at the point corresponding to the mean of the two qualities. The triangle was created from two lines drawn from this vertex to pass through the points corresponding to the two quality percentages. A similar procedure was used for a block with three consecutive quality classes: the vertex was fitted to the mean value of the three qualities and the triangle was created by joining all the points corresponding to the quality values prolonged along the vertical axis. Note that in the case of three qualities, in order to ensure a total of 100%, it may be necessary to recalculate some of the quality percentages (as can be observed in Figure 2 (c)).

The results of the fuzzy kriging application were also mapped as a triangle, translated into percentage terms as follows: a triangle with a base drawn to represent a single quality represented a block that consisted entirely of a single given quality, a triangle with a base corresponding to two or more qualities corresponded to a block with percentages that corresponded to the values in the Y axis of the prolongations from the X axis for each quality.

Kriging with imprecise data: fuzzy kriging

Kriging, which belongs to the group of spatial estimators, is traditionally applied to hard data. Important references to this technique include Cressie (1993), Journel and Huijbregts (1978) and Chilés and Delfiner (1999). Fuzzy kriging is a generalization of the kriging methods that use hard and soft information. Bardossy et al. (1989) distinguish between three types of fuzzy kriging according to types of input data and variograms:

- Fuzzy kriging type 1, with both hard and fuzzy data and crisp variogram.
- Fuzzy kriging type 2, with hard data and fuzzy variogram.
- Fuzzy kriging type 3, with both hard and fuzzy data and fuzzy variogram.

A methodology developed by Diamond (1989) makes it possible to both estimate spatially distributed fuzzy numbers and calculate the estimation variances. This was the method we used to make the three-dimensional estimates of the quality percentages for the granite blocks. The spatial dependence of the fuzzy triangular data is modelled by the lower, modal and upper crisp variogram (or covariogram) functions. The lower, modal and upper crisp variograms are determined using the left, modal and right values of the triangules, respectively. An appropriate kriging system, combining the three functions, has to be solved for every new location x of interest. The solution of the system is a vector of weights $(\lambda_1(x), \lambda_2(x), \ldots, \lambda_n(x))$ and then the kriging estimator is calculated as

$$\hat{Z}(x) = \sum_{i=1}^{n} \lambda_i(x) Z(x_i)$$

where $\hat{Z}(x)$ is the estimated fuzzy value for the position x, $\lambda_i(x)$ are the crisp minimizing parameters and $Z(x_i)$ are the input fuzzy values observed in the input coordinates x_i.

The kriging estimation variance for the location x is determined by

$$\sigma^2(x) = C(0) - \sum_{i=1}^{n} \lambda_i(x) C(x_i - x)$$

with C a function calculated from lower, modal and upper crisp variogram functions. As can be deduced from this last equation non-fuzzy values are achieved for the kriging variances.

Note that, even though the support is the block, we implemented point fuzzy kriging rather than block fuzzy kriging, given that both the input and output data referenced by the three-dimensional coordinates were the central points of the 1000m^3 blocks. Associated with these coordinates was a triangular fuzzy number indicating the approximate quality of the entire block.

Input data is referenced by the three-dimensional coordinates of the central points of the 1000 m^3 blocks. Associated with these coordinates there is a triangular fuzzy number indicating the approximate quality of the entire block. Output data estimated by the kriging algorithm is of the same kind. That is to say, triangular fuzzy numbers associated to central points of non observable blocks.

We adapted the method proposed by Diamond (1989) to anisotropic data. Working with anisotropic data is the usual situation when estimating by kriging methods with hard data. When fitting the lower, modal and upper crisp variogram (or covariogram) functions, the anisotropic behaviour of the input data has to be detected and then modelled in a similar process as the one used for crisp data.

3. RESULTS

Field data was organised spatially and saved in a database in which each block was identified by the spatial coordinates for its central point and characterised by quality class percentages. A total of 35,543 data cells were used for the interpolation. For the study area as a whole, the quality percentages calculated were as follows: top grade rock 16.24%, secondary grade rock, 15.46%, and tertiary grade rock (semiblocks) 9.09%. The remaining 59.21% was aggregate quality rock. The total yield of 40.79% was a reasonable yield for an exploitation to be considered economically viable.

For each of the input cells a triangulation function was applied to the quality percentages with the aim of constructing a triangle that reflected quality delimitations—equivalent to assigning a fuzzy number representing the quality of the block to each cell. For the data overall, the fuzzy triangular number referred to a single quality class in 87.17% of the cells, two quality classes in 12.5% of the cells, and three quality classes in only 0.33% of the cells. After applying triangular functions to each block, the percentages obtained for each quality class were as follows: top grade 14.37%, secondary grade 16.29%, tertiary grade 13.07%, and low grade 56.27%. As can be observed, there was a slight modification in the overall percentages, with small falls in the top and lowest grade classes and slight increases in the intermediate grades.

The 35,543 triangular fuzzy numbers represented the set of input data for the kriging estimation. Applying the methodology developed by Diamond (1989), three experimental semivariograms were fitted to the triangles: one to the lower extremes, another to the modes and a third to the upper extremes. We consistently found that the parametric model that best modelled the spatial dependence was the spherical semivariogram without nugget effect. In order to reflect the direction of the fractures in estimating the qualities, an ellipsoid was used whose longest axis corresponded to the preferred fracturing direction. Figure 3 reproduces the discontinuities mapped in the mass and a stereogram showing all the studied diaclases. The predominant fault orientation corresponded to a set of conjugated faults running NNE-SSW, although there were other faults running NE-SW and NW-SE—also conjugated but of lesser importance. Fault plane dips varied between 70º and 90º. Representing the anisotropic behaviour of fractures was an innovation in the Diamond (1989) methodology which required the fitting of several different directional semivariograms with a view to detecting the ranges for the experimental semivariograms.

Figure 4 shows the experimental and theoretical modal crisp variograms in the three main anisotropy directions. Spatial dependence of the fuzzy triangular data is modelled by the 3-D ellipsoid determined by the fitted variograms. Lower and upper crisp variograms are not shown as they are quite similar.

After modelling the functions, fuzzy kriging systems of equations were applied to obtain a reserve estimate. The algorithms used to resolve the kriging systems of equations were programmed from the source code of the public-domain GSLIB programs. These programs, duly code-modified, can be adapted to the estimation of triangular fuzzy numbers with anisotropic behaviour. Deutsch and Journel (1998) are an important reference in regard to the use and functioning of three-dimensional kriging for non-fuzzy data.

Output data was represented by fuzzy quality triangles (fuzzy numbers) for 1,262,539 blocks and the kriging estimation variance. Among the points obtained, those outside the domain were excluded. The data underwent three processing phases— conditioning, filtering and calculation—with a view to completing a detailed estimate of the deposit.

Conditioning and filtering consisted of adapting the characteristics of the points—spatial coordinates, estimation variances, vertices of the quality triangles and identification with quality percentages (applying the procedure explained in Section 2.2.b.)—so that they could be saved in specific database fields and thus be distinguished from points whose Z coordinates were located above ground.

The results were then calculated, both for the entire studied area and for different horizontal planes of the deposit from the lowest altitude defined by the borehole base and the upper altitude (285 m) by the outcrop surface.

Reserve estimation was performed for a total volume of 124,109,970 m^3, of which 13.89% corresponded to quality 1, 15.96% to quality 2, 21.59% to quality 3 and 48.56% to quality 4. Figure 5 illustrates the quality distributions for different horizontal planes (by way of example, at altitude intervals of 65 metres). It can be observed that quality distributions depended on depth in the batholith. The highest areas of the deposit (closest to the weathering layers) had the lowest percentages of the top 2 grades of rock, which were to be found in greater proportions in the deeper parts of the deposit.

Figure 6 shows a section of the deposit and the qualities assigned to each block. In this graph the block is assigned the quality that is most representative. We have not been able to compare results with reality as yet, except at the work fronts, which is where exploitation commences and where there is total concurrence between estimated and real values. This is logical, as samples were taken at the fronts. We would have to wait about 10 years to get overall results.

Kriged model output was improved using a graphic application that facilitated the Identification of areas of interest from a commercial quality perspective. This improvement (which is independent of the proposed method) consisted of programming (in Microsoft Data Base, and for the same output database) a series of queries in Structured Query Language (SQL) that represented, in the 3D, the set of blocks within the deposit. These queries retrieve immediate information on each of the blocks. SQL also enables more detailed information to be obtained on the reserve estimation, structured according to horizontal planes whose Z coordinates coincide with the Z coordinates for each of the levels defined by the points cloud. Figure 6 illustrates the results of this programming, in a format that depicts quality distributions on a block-by-block basis. This facilitates decision-making in regard to the selection of new areas for exploitation based on economic criteria.

4. CONCLUSIONS

We describe the results (too concise) of the application of a novel methodology for assessing reserves of ornamental rock, based on combining fuzzy logic and kriging techniques. The advantage of the method is that it estimates the distribution of different commercial ornamental rock qualities in the primary block. Moreover, it takes into account that a block may contain more than one commercial quality class, which precludes the sub-estimation arising from the consideration that a primary block (measuring 1000 m^3) consists of only one quality class. The kriging approach to estimating commercial rock qualities incorporates two new features. Firstly, a fuzzy mathematical approach to assigning qualities to each block reflects the fact that fracturing in quantitative and qualitative terms affects blocks progressively, resulting in gradual changes in commercial quality grades with no clear cut-off points. Secondly, fracturing anisotropy at the deposit scale is taken into account, and given that quality is largely determined by fracture distribution, this enables a real spatial estimate of quality to be obtained.

This methodology, which was applied to one of the world's most important deposits, represents an advance on the existing techniques used to estimate ornamental rock reserves, as it leads to a more realistic estimate that is based on considering the exploitation method, deposit anisotropy, and fuzzy boundaries between commercial quality classes.

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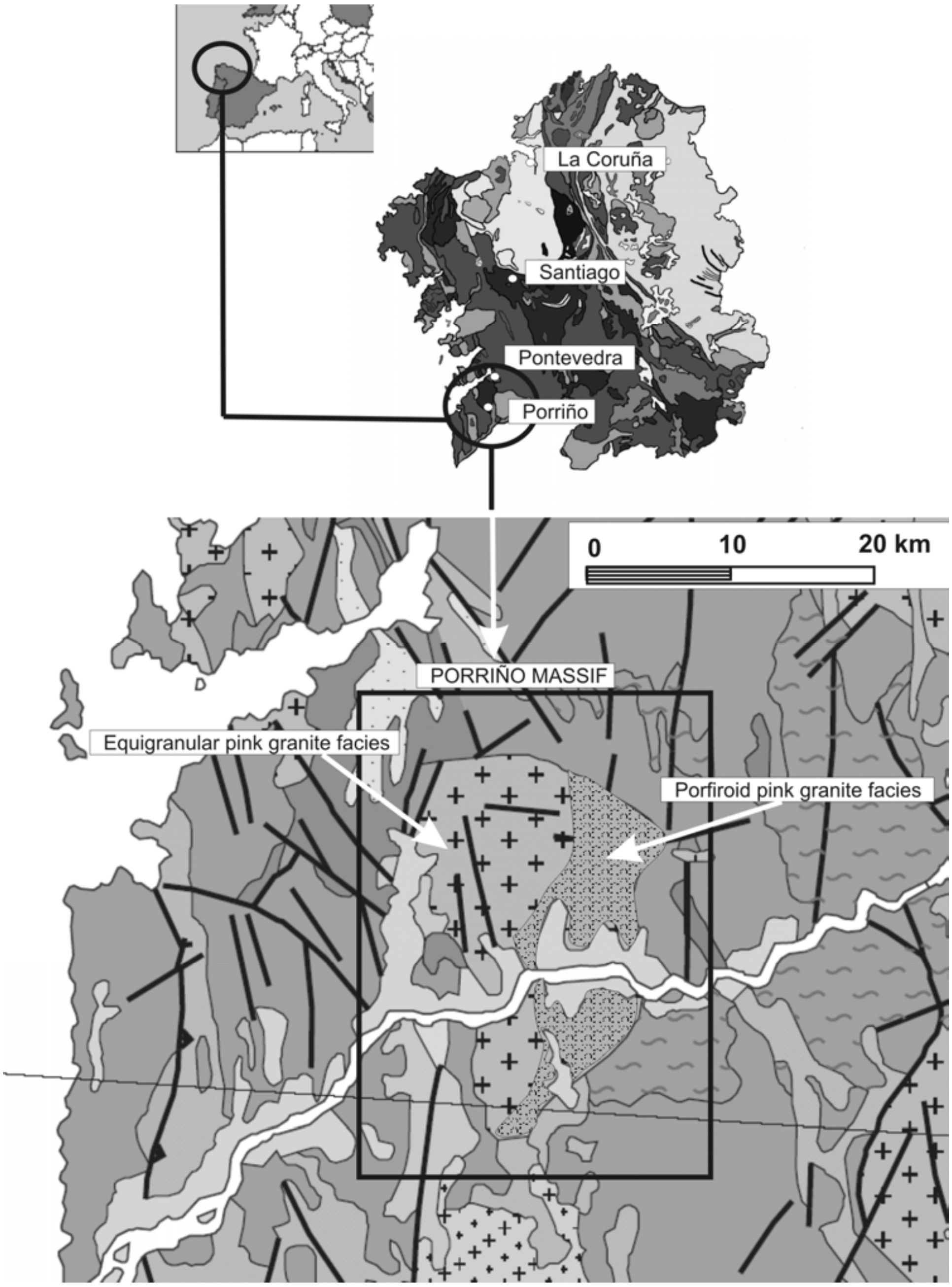

Figure 1. Geographic location of the deposit to which the proposed reserve evaluation method was applied (left). Geological map of the two massif facies (right); the boundary between the two facies is the eastern limit of the studied area.

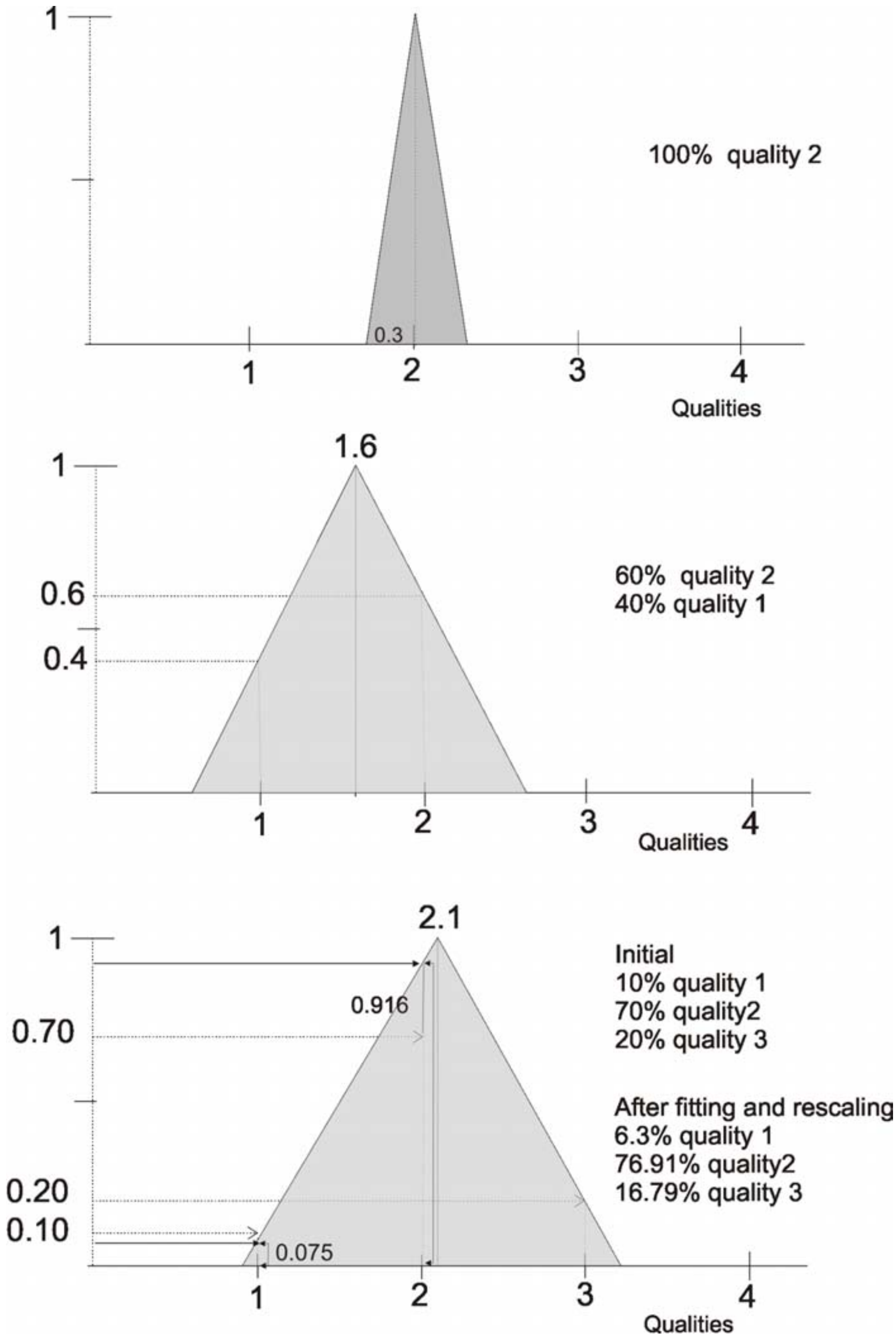

Figure 2. Appointment of triangular membership functions for quality percentages defined for three different blocks: (a) block yielding a single commercial quality; (b) block yielding two commercial qualities; and (c) block yielding three commercial qualities.

Figure 3. Map of diaclases in the Rosa Porriño massif and stereogram (inset) of discontinuities.

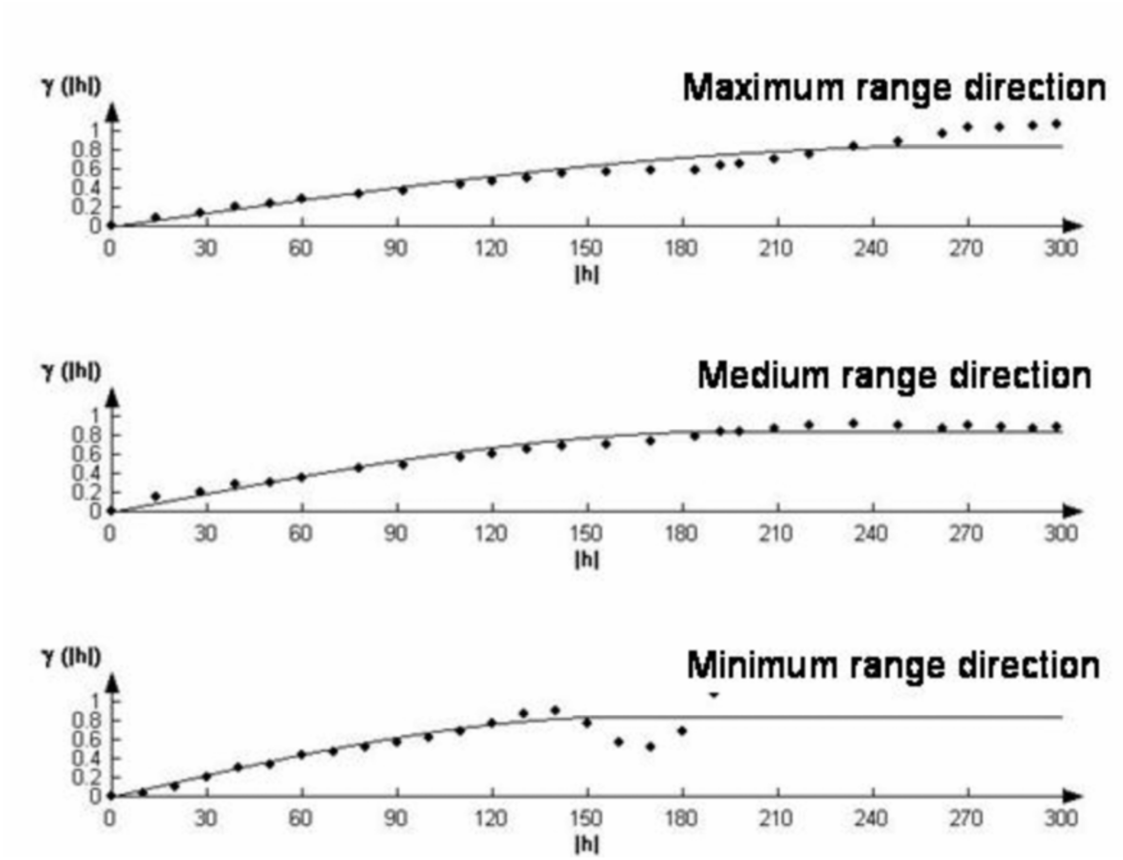

Figure 4. Experimental and theoretical modal crisp variograms in the three main anisotropy directions.

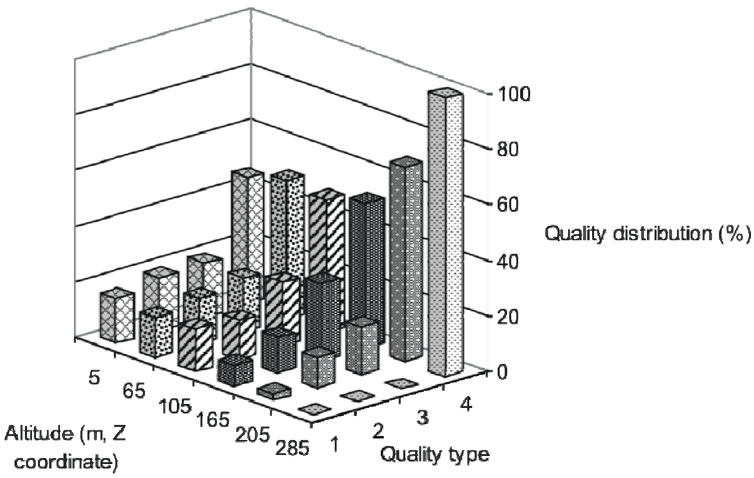

Figure 5. Distribution of qualities for different deposit horizontal planes, showing percentage values for each quality class (1 to 4), for 6 horizontal planes, from the lowest (5 m) to the highest (285 m) limits of the Z coordinate.

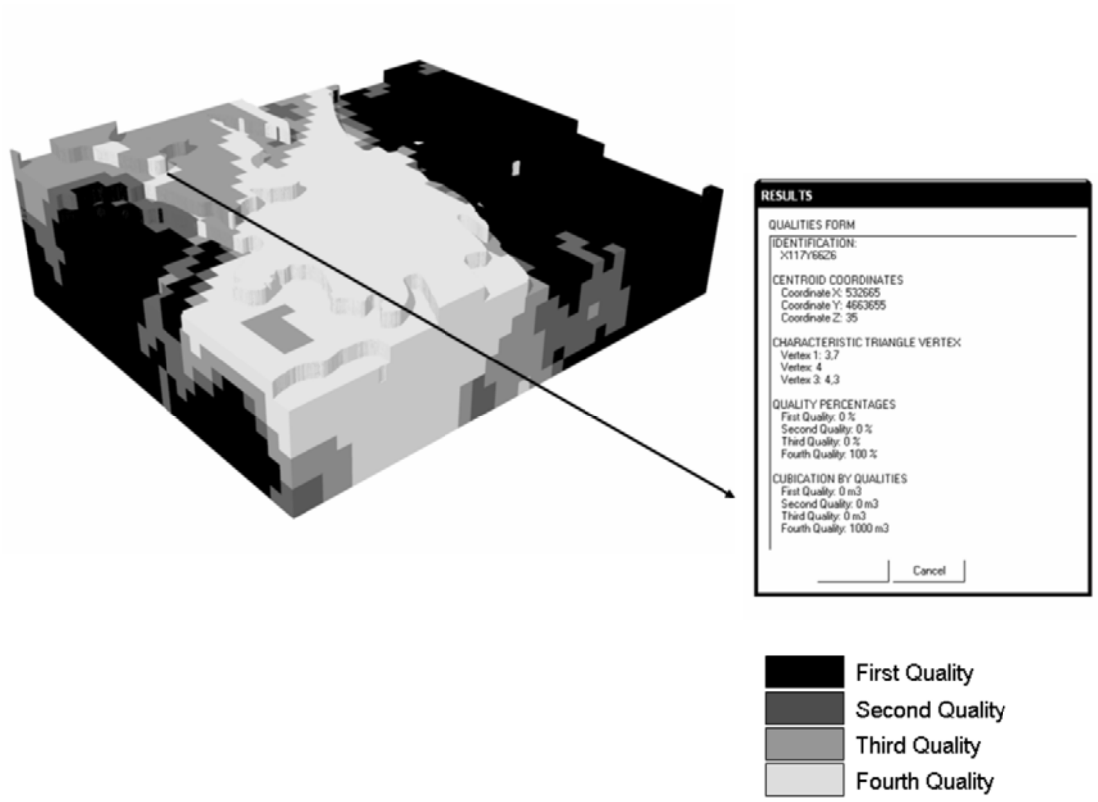

Figure 6. Partial overview of the deposit block model and result of a database query in regard to the estimated qualities of a block.