



Decision criteria for the exploration of ornamental-stone deposits: Application to the marbles of the Portuguese Estremoz Anticline

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Received 8 June 2007; received in revised form 6 January 2008; accepted 17 January 2008

Available online 11 March 2008

Abstract

Ornamental stones are almost ready-made raw materials with a high economic value for the building-construction industry. The discovery of new near-surface deposits, the very low exploitation efficiency, the huge amounts of wastes produced, and the land-use accessibility conditions are the main challenges that the extractive industry for this mineral resource is facing nowadays. Research on advanced geological exploration tools and methodologies is needed to reply to those challenges.

During the process of geological ornamental-stone deposits exploration, the unique and decisive criteria that should be considered are its dimensions, homogeneity, and fracturing state. Lithostructural geological mapping and in situ fracturing surveys are the basic indispensable tools for their field assessment. By applying these criteria and tools to a marble-rich area in the Portuguese Estremoz Anticline and a step-by-step numerical evaluation of the qualitative geological parameters, the delimitation of the best target areas for exploitation or environmental rehabilitation has been effectively mapped.

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Keywords: Ornamental stone; Marble; Geological exploration; Estremoz anticline; Portugal

1. Introduction

The methodologies and techniques for geological exploration have evolved through the times in close relation with the research needs on metallic ores and hydrocarbon resources. The large economic profits associated with the discovery of this kind of deposits justify the large investments involved in their exploration and, concomitantly, the development and evolution of those methodologies which today are indispensable and highly sophisticated, making use of geological, geophysical, geochemical, and remote-sensing techniques.

However, there is a vast difference when analysing the industrial mineral-and-rock resources, particularly the mineral raw materials, used in the building and construction industry. Being extensively available, as they are common in nature and appear at low depths, these materials are not the objects of huge exploration investments, nor do these

materials permit the investment, given the fact that they generally represent a high-volume, low-value commodity. As a consequence, adequate exploration methodologies have not been researched for this type of resources in spite of the high level of technological development that has been achieved for exploitation operations.

This is also true for the specific sector of Ornamental stones. They are almost ready-made raw materials for the building-construction industry, but unlike other common building-industry raw materials, they have a large economic bulk value that depends on the decorative function for which they are used. In addition, they also support an international trade market that is fast growing.

The classical challenges for this sector are the very low efficiency and productivity of the exploitation and transformation processes, and the huge amount of wastes that are produced, often more than 70% of the total raw material extracted. These issues have been studied by the classical material–life cycle analyses approaches that span the entire life-cycle, from the production stage to the recycling stage, and which, from the geological point of

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view, really begins in the puberty stage as they do not consider the exploration stage. Another practical challenge is an economic regulation for the sector correlated with the present day efforts on standardisation, namely those on certification of the innumerable varieties of commercialised stones, which result in the large amount of published reports and papers about their technical properties. However, for the future sustainability of the ornamental-stone sector, two other main challenges must be considered; they are the discovery of near-surface deposits to supply and secure the market needs, and the solution to the problems related to the land-use accessibility conditions that are common to all extractive industries. The resolution of all these challenges is dependent on the acquisition of an appropriate geological knowledge about ornamental-stone deposits, and that is accomplished by the geological exploration process. Therefore, for the life-cycle analysis of ornamental stones and for the sustainability of the sector, a different approach that begins from the exploration stage, not the exploitation stage, should be envisaged. Mineral resources, before being exploited, must be discovered.

Research and development are needed with respect to advanced geological-exploration tools and methodologies especially directed to ornamental-stone deposits. As the existing reports on this subject are scarce, this work aims to present what we consider to be the decisive geological-exploration criteria for their evaluation. The marble deposits of the Portuguese Estremoz Anticline are presented as a case study. This is perhaps the first-written English text on the general geological features of the Portuguese Estremoz Anticline, and on the detailed marble-resource evaluation of one of the mining land-use planning units in that region of the Portuguese territory.

2. Ornamental stones: definitions and scope of use

2.1. Ornamental stones/natural stones/dimension stones

Companies operating in the extractive industry of ornamental stones are small- and medium-sized enterprises, with a strong link within their own commercial-activity circle, most often directly with the end-user. This relationship is responsible for the nonconsensual proper names for the sector, the common designations being ornamental stones, natural stones, and dimension stones.

“Dimension stones” is a designation commonly used in Anglo-Saxon countries. It was, perhaps, the first name to be attributed to this sector, having been used for the first time by Bowles and Coons [1], to distinguish it from the “aggregates sector”. The distinction proposed by these authors, and later developed by Currier [2] and Barton [3], forms the base of the American Society for Testing and Materials’ C119-Standard Terminology Relating to Dimension Stone, which is concerned with the shape and size requirements of the final product. The stones are

considered essentially as building-construction materials with a structural function.

The designation “natural stones” is a recent term used within the South European countries to valorise the stones as a natural product—in the “as it is” condition—without transformation, as retaliation against the commercially aggressive ceramic sector.

“Ornamental stones” seems to be a more appropriate denomination to this sector, because it signifies not only the commercial objectives but also the end-use of this raw material. By the term “ornamental”, an economic added value is implicit as well as the final use of the stones, which, nowadays and contrary to other building materials, is mainly for aesthetic purposes. Therefore, “ornamental stones” can be defined as mineral resources used as building raw materials with both structural and decorative functions. This definition embraces all types of rocks with the most assorted sizes and shapes, from the small cubes used in street pavements to the thin slate plates used as roof tiles or wall coverings, and additionally, the large blocks exploited for use as coverings and pavement slabs, and for use in statuary, funerary art, etc. They all have some kind of structural function but the main purpose is a decorative/ornamental one.

2.2. Scope of use for ornamental stones

Ornamental stones can be subdivided into six groups [4]: granite, limestone, marble, quartz-based stones (sandstone, quartzitic sandstone, and quartzite), slate, and others (infrequently used types). Depending on their physical and chemical-mineralogical properties, restrictions on the use of ornamental stones are imposed, particularly with respect to the indoor versus outdoor applications and private- versus public-building applications. In countries where negative temperatures and high thermal amplitudes are common, the outdoor use of stones with a weak resistance to the laboratory freezing-and-thawing assays must be avoided. However, they can be used indoors. Similarly, less resistant stones should not be applied on pavements of public buildings but can be used in private habitations, where walking is not as intense as in public places. Another common bias is to associate the ornamental aptitude of the stones to their capacity to admit a good polishing, which depends on the mineralogical composition and texture of the stone. Notwithstanding this fact, nowadays coverings with unpolished stones are common, and they still retain their decorative function.

These considerations show that the decision about a particular rock being an ornamental variety does not depend on its technical specificities. Hence, these properties are not the criteria to be considered during the geological-exploration stage of ornamental stones. The aesthetics of the stones is the intrinsic factor on which depends their use as construction materials with decorative functions. Even being strongly subjective, aesthetics can be used for the technical evaluation of ornamental stones because it is the

result of the conjoined perception of a set of criteria, namely the colour, the texture, and the presence or absence of discontinuities. Although these are fashion-dependent criteria, particularly the first two criteria, they are technically objective, rendering the homogeneity degree of the stones as the criterion on which their individual appreciation in terms of aesthetics depends. The homogeneity degree is particularly relevant during geological surveys as it is the base for the dimensioning of the ornamental-stone deposits: a specific volume of rock with homogeneous characteristics and a specific spatial disposition.

3. Exploration of ornamental stones

Scientific reports about research on the exploration methodologies for ornamental stones are scarce. The *Manual de Rocas Ornamentales* [5] and *Stone: Building stone, rock fill, and armourstone in construction* [6] are in our opinion the most complete scientific studies regarding this subject. Both present a very detailed systematisation of the research stages for the discovery and evaluation of ornamental-stone deposits from the initial data-

compilation stage to the quarry-project stage. In synthetic terms that do not differ from the general methodology adopted for other kinds of mineral raw materials, these stages are as follows:

- *Stage 1*: Compilation of the available information and planning of the works;
- *Stage 2*: Generic geological survey and selection of target areas;
- *Stage 3*: Characterization and valuation of the selected areas;
- *Stage 4*: Detailed characterization of the deposits; and
- *Stage 5*: Exploitation project.

In this work sequence priority has been attributed by García [7] to the geographical features of the target area and the characterization of the lithologic units as the main factors to be considered in the decision-making process, mainly through parameterizing and weighing several criteria such as the deformation state of the rocks, their colours, textures, and weathering degree. Smith [6] emphasises a detailed geological-field mapping as the base for good exploration prospects and its supporting geophysical sampling tools and methodologies.

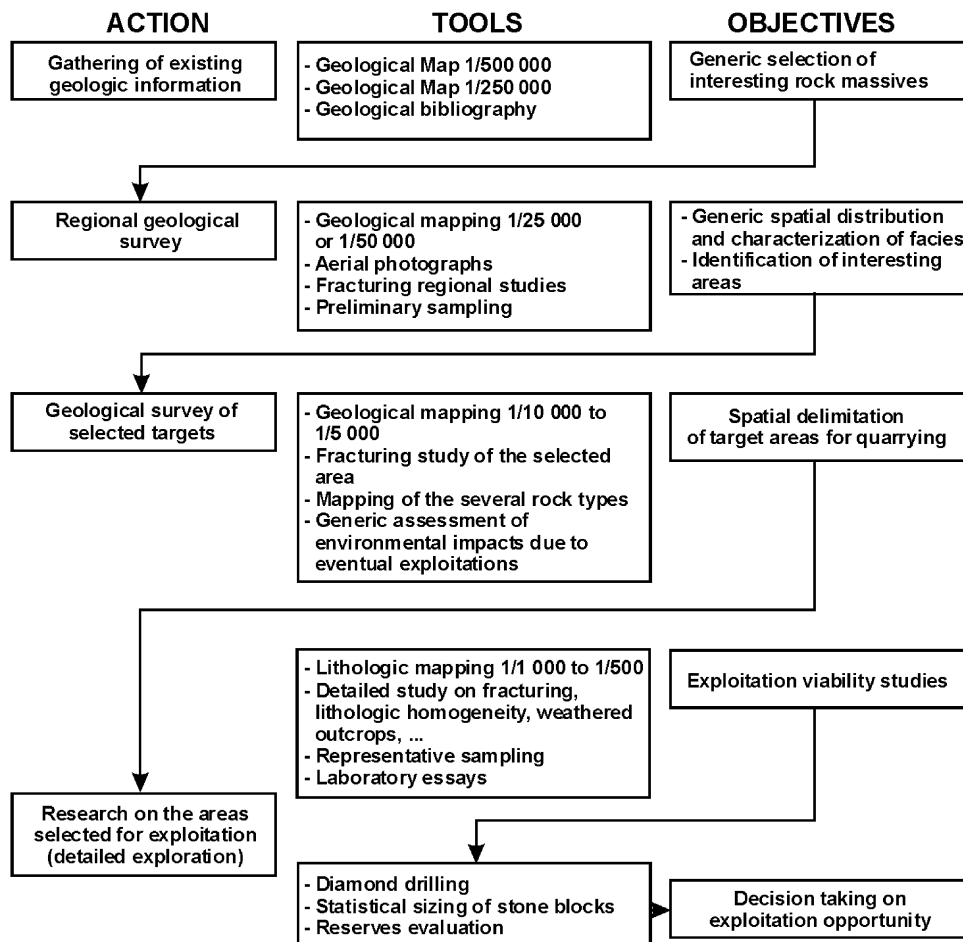


Fig. 1. Work sequence for the exploration of ornamental stones (adapted from [8]).

The details of the procedures, which imply the working scale for the characterisation and assessment of the above-mentioned criteria, increase along the working sequence, as seen in another methodological proposal [8] represented in Fig. 1. More recently, some authors have presented quarry evaluation-addressed methodologies that can be applied to the exploration stages to some extent [9–13].

A compilation of the criteria to be considered during the different exploitation stages is presented in Table 1, on the basis of proposals by several authors [6–8,14–16]. Some peculiarities can be pointed out in this table when considered along with the working sequence presented in Fig. 1, namely that priority is always given by these authors to the results of the assays on the physical–mechanical properties of the rocks for the decision-making process on their viability as ornamental stones and the fracturing of the rocks as parameters to be considered almost in all the exploration stages.

Table 1
Main criteria to be considered during ornamental stones exploration

Morphology	<ul style="list-style-type: none"> ● Geological limits ● Thickness and thickness variations changes ● Lateral facies changes ● Karst areas
Structure	<ul style="list-style-type: none"> ● Bedding, cleavage and schistosity, lineaments, etc. ● Faults, joints ● Folds
Fracturing	<ul style="list-style-type: none"> ● Directional families ● Family spacing ● Fracturing density
Metamorphism	<ul style="list-style-type: none"> ● Type ● Zonation ● Mineralogy
Lithologic characteristics	<ul style="list-style-type: none"> ● Mineralogical and chemical composition ● Colour ● Grain size ● Texture ● Re-crystallizations, <i>Schlieren</i>, fossils, etc. ● Homogeneity (colour, texture, fossils and other discontinuities) ● Oxidations and other weathering alterations ● Physical–mechanical properties (water absorption, volumetric weight, compression breaking load, etc.)
Exploitability	<ul style="list-style-type: none"> ● Reserves ● Accessibility (topography, roads, distance to consumer centres, environmental protected areas) ● Overburden and/or weathering zone thicknesses ● Environmental impact ● Industrial infrastructures ● Established extractive industry ● Market demand

3.1. Decision criteria

On the basis of the exploration experience of the authors of this study with limestones, marbles, and slates for ornamental purposes [17–23], the factors affecting the viability of rock masses for ornamental-stone production have been confirmed to be solely related to the *dimensioning* and *homogeneity* of the lithological units and their *fracturing* degree. Therefore, these can be considered as being the decision criteria for ornamental-stone prospecting (Table 2). The remaining criteria of geologic nature listed in Table 1 have only a secondary role when considered individually because they are not exclusion factors. They are important as the basic qualifications required for the final use and commercial evaluation of the stones but they do not compromise the suitability of the rocks as ornamental stones. Thus, the ornamental suitability of a rock does not depend on its colour, when taken independently, because this is a fashion-dependent aesthetic criterion. Additionally, the ornamental suitability of a rock does not rely on its mechanical characteristics because these are criteria for the qualification of the rock's final use. Moreover, the geographic locations of their occurrence can make their exploitation impracticable, but these details are extrinsic to the mineral resource.

3.2. Field evaluation of decision criteria

The field evaluation of the above-mentioned decision criteria is carried out by two basic geologic tools: geological mapping and fracturing survey.

Thematic geological mapping, with strong support from the techniques of structural geology and diamond-core drilling, is fundamental for the research and evaluation of data that are intrinsic to the dimensioning and homogeneity qualification of the deposits. To be effective for the exploration of ornamental deposits, geological mapping must be directed to the identification, delimitation, and characterization of suitable areas, which should correspond to the existence of at least one homogeneous lithologic unit with a thickness and a total volume that permit the retrieval of commercial-sized rock blocks for a specific period of time. Smith [6] presents a panorama of the

Table 2
Decision criteria on the exploration of ornamental stones

Dimensioning	Homogeneity	Fracturing
<ul style="list-style-type: none"> ● Thickness of the productive units (sedimentary beds, metamorphic facies, etc.) ● Volume of the deposit ● Spatial disposition 	<ul style="list-style-type: none"> ● Colour ● Texture ● Discontinuities 	<ul style="list-style-type: none"> ● Preferential directions ● Frequency ● Density ● Intensity ● Type and morphology

geophysical methodologies that can play an important role in this process. Particular attention must be focused on the scale of work at various stages of the exploration process, lithology, geologic structure, and conventions and terminology used. For the thematic maps to be useful, the conventions and terminology should be understandable by the audience to which they are directed.

Regarding fracturing, primary importance must be given to the direct method of in situ fracturing-data survey, as it is an essential tool for the decision about the viability of a deposit for ornamental-stone production. The methodology to be adopted for this in situ collection of data about the orientation and morphology of fractures is constrained by the following factors: the dimensions of the exploration area; the lithology; and the size, shape, and placement of the outcrop. The more common methods are based on the survey of all the fractures enclosed in a specific circular or rectangular area. For quarry-wall surveys, the *scan-line* method is particularly suitable for collecting data of all fractures traversed by a specific line drawn on the wall. The dimensions of the area or the *scan line* are dependent on a preliminary subjective evaluation about the spacing between fractures of the same family.

The most important data to be collected regarding the fractures are orientation (strike and dip), length, continuity, size and mineral filling of apertures, spacing, and host lithology. For each one of these parameters, there are several methods of data analysis and result presentation, more common being a combination of the usual descriptive statistics tools and the suggested methods of the International Society for Rock Mechanics [24]. The discernment of the main fracturing-directional families is one of the most important deductions to be carried out as it is the departure point in the determination of the fracturing frequency for each family. The results are decisive as they determine the discrimination between suitable or unsuitable areas for the production of large blocks of rock.

Considering the frequency of fracturing data as a regionalized variable [25], that is a function that depends on spatial position, it can be the object of a geostatistical approach using the semivariogram model and kriging estimation of the values between sampling stations [26]. This geostatistical approach to the linear frequency of fracturing data is scientifically supported by well-known techniques for the evaluation of ore concentrations as a function of the spatial sampling distribution and permits the mapping of the spatial distribution of the estimated frequency [27,28]. This cartographic possibility, in combination with geologic mapping, yields very useful data for the delimitation of the more suitable areas for ornamental-stone exploitation.

Depending on the exploration stage, the in situ fracturing survey can preliminarily be supported by indirect methods such as remote sensing and geophysical methodologies and tools. Common remote-sensing tools include satellite imagery, similar to that of the Landsat thematic

mapper, and aerial photographs as they are good aids in the initial surveying stages. Their combination permits the distinction between more or less fractured regions and the definition of the regional fracturing pattern. *Google EarthTM mapping service* is a recent remote-sensing tool with tremendous capacities as it grants the user a simulated three-dimensional view with zoom capabilities and the ability of an interactive management of the orientation view. Although not being geographically precise, it can be a very effective tool for the selection of exploration-target areas of ornamental stones as a function of the fracturing degree of the rocks.

Geophysical methodologies are important in the more detailed research stages as a complement to the in situ fracturing surveys. Seismic methods, in general, should be considered along with the very low frequency electromagnetic/radio frequency electromagnetic (VLF-EM/RF-EM) and the ground-penetrating radar (GPR) methodologies. All methods have advantages and disadvantages regarding the type and detail of the information data obtained, execution speed, and costs.

A recently developed seismic methodology is herein explained because it has a low cost and fast execution speed. It consists of the execution of seismic profiles for the acquisition and statistical treatment of data related to the azimuthal variation of the velocity propagation of seismic waves and the respective morphology [29]. It yields very effective results for the determination of the fracturing degree of rocks in regions where the outcrops are so scarce that the direct-survey methodology proves ineffective.

The VLF-EM/RF-EM method is based on the propagation of low- to very low-frequency radio waves that generate a secondary electromagnetic field dependent on the lithology. The detection of this secondary field allows the acquisition of data about the propagation environment and its heterogeneities: clay-filled fractures, karst, paleochannels, lateral facies variations, etc. [30,31]. This method has a low investigation depth but can be quickly carried out with a very low cost, allowing the acquisition of data related to major structures [32,33] and the delimitation of suitable area targets for more advanced ornamental-stone exploration stages.

GPR is an electromagnetic method that uses high-frequency (10 MHz–2.5 GHz) pulsed radio waves for shallow, high-resolution, subsurface investigations of the earth. In spite of having a low penetration capacity, the application of GPR to ornamental-stone prospects is due to its resolution performance for detecting small-scale features such as fractures and bedding planes. It has been used to locate fractures on granitic rocks since the beginning of the 1990s and its performance is highlighted in the detection of horizontal and subhorizontal fractures on igneous plutonic rocks [34]. At the least, rock masses should be homogeneous and not be marked by internal structures because these markings could lead to misinterpretations [16,35].

4. The Portuguese Estremoz Anticline marble-production centre

The Estremoz Anticline (Fig. 2) is an antiform with an arcuate morphology and a curvilinear axis that plunges into the NW and SE terminations. It is a macrostructure of the Portuguese territory, where the main Portuguese production centres of ornamental marbles are located. These belong to the Estremoz volcano-sedimentary carbonate complex [36], which is part of the Ossa–Morena tectonostratigraphic unit [36–41]. This complex of the Ordovician age [36,42,43] is underlaid by a Cambrian dolomite formation and overlaid by Silurian green schists with liditic intercalations (Fig. 3).

The Ossa–Morena Variscan unit underwent a complex structural evolution mainly governed by transpressional tectonics under sinistral wrench conditions [40,41,44]. Although this tectonic regime was continuous [43,44], two main diachronic and noncoaxial deformation episodes (D1 and D2) are usually distinguished. In the Estremoz Anticline, the D1 episode of the middle Devonian age [45] resulted in the origin of isoclinal recumbent westward-verging folds with N–S oriented axes that can be observed at outcrop scale. Schistosity, with bedding transposition, developed during this episode, which is also responsible for

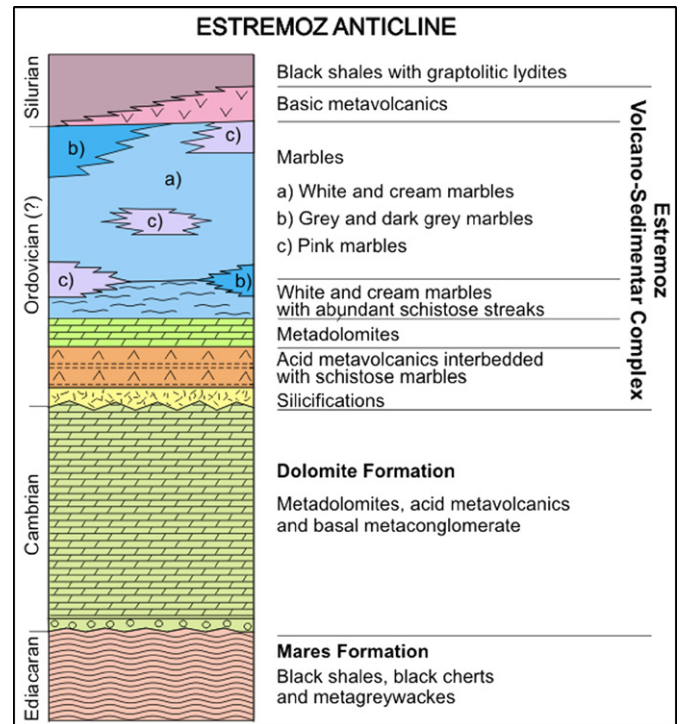


Fig. 3. Simplified lithostratigraphy of the Estremoz Anticline.

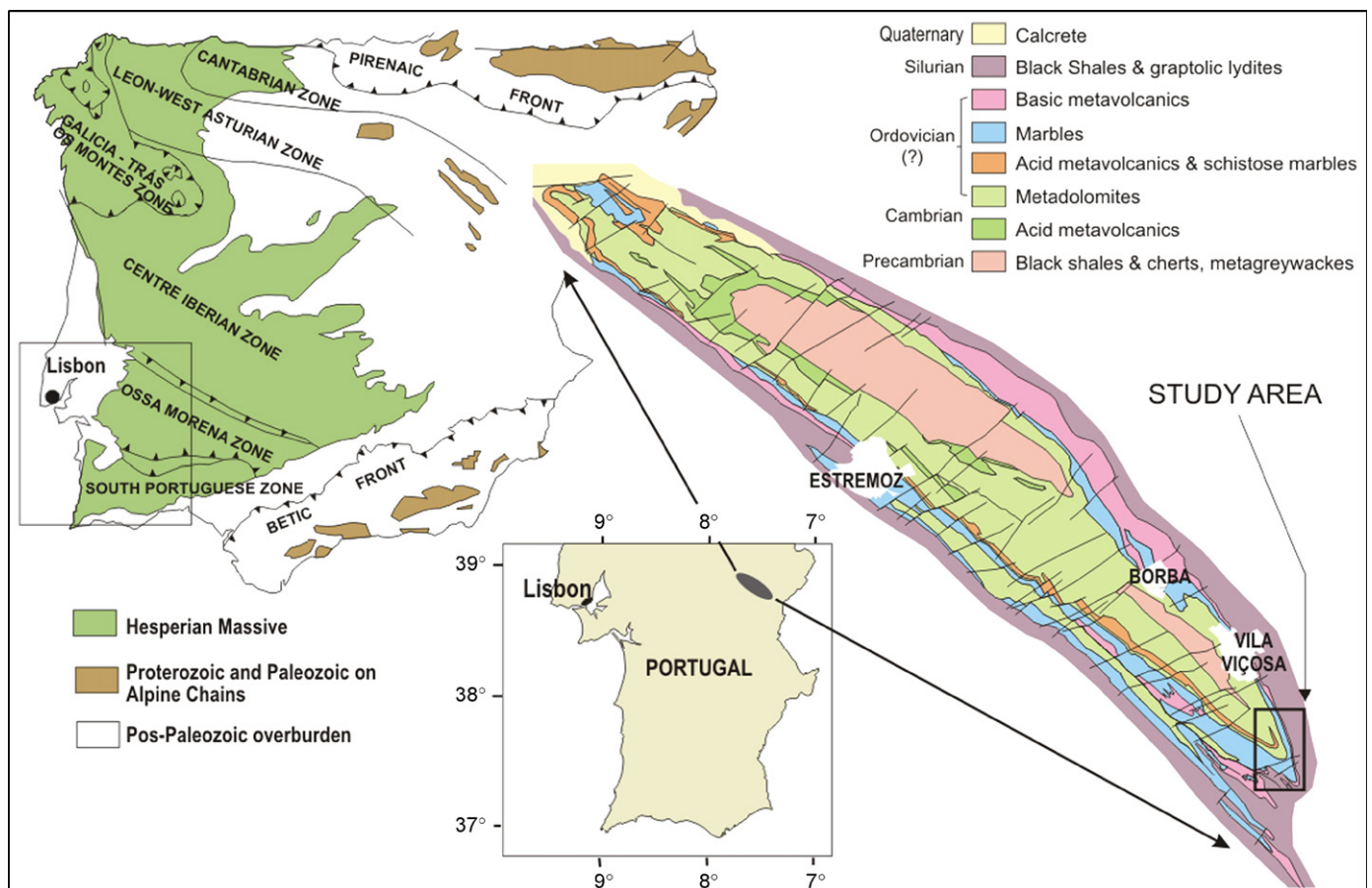


Fig. 2. The Estremoz Anticline in the geological context of Iberia and location of the study area.

the low-grade regional metamorphism (green schist facies) affecting rocks [46]. Episode D2 of the Upper Carboniferous age [39] led to the development of a regional trend of NW–SE oriented fold axes with SW high-inclined axial planes and an associated fracture cleavage. These NE-verging folds have stretched limbs, which can be assigned to progressive deformation. They are observed at all scales, the second episode being responsible for the present regional macrostructures. The superposition of these folds with the older structures resulted in the Ramsay's [47] type 2 and type 3 fold–interference patterns.

The ending stages of D2 are associated with the development of NW–SE left-lateral shear zones showing deformation stages from ductile to fragile [43]. Their occurrence is discrete and they preferentially re-form the stretched limbs of the folds confirming the progressive and continuous character of the tectonic events.

The ending of the Variscan orogeny, or even the beginning of the Alpine orogeny, is associated with a network of fractures, preferentially NE–SW oriented, and the emplacement of dolerite dikes. Similar to the previous-mentioned shears, these fractures segment the Estremoz Anticline into compartments.

The exploitation of the marbles from the Estremoz Anticline started during the occupation of the Iberian Peninsula by the Roman Empire, but only in the last few decades has it become intensive, leading to significant landscape disorders and environmental risks to an important *karst* aquifer system that supports the public water supply in the region. Taking into consideration the socio-economic importance of marble exploitation, a regional land-use planning was implemented in this region [48] and five planning units were delimited within it, regarded as the main exploitation centres.

The Estremoz Anticline geology is available through a few geological studies and maps of regional scope [42,43,49–56]. They revealed insufficient to the resolution of the problems within each land-use planning unit, with reference to the requirements of both the extractive industry and the environmental authorities: definition of the most favourable areas for quarry development and for waste deposition, environmental rehabilitation areas, aquifer system protection, etc. Exploitation of these marbles was always carried out empirically, without any adequate geology-based knowledge, as is common practice worldwide for the ornamental-stone industry. To deal with this situation, detailed geological studies were carried out in each planning unit by applying the current knowledge about ornamental-stone exploration methodologies, with particular emphasis on the decision criteria mentioned in the earlier sections. The following section aims to present the procedures and results obtained for the Pardais planning unit, which is a part of a large study conducted by the Portuguese Geological Survey [23].

5. The Pardais land-use planning unit

The Pardais land-use planning unit is an area of 413 ha located on the SE-periclinal termination of the Estremoz

Anticline (Fig. 2). It holds 21 quarries strongly constrained in space, half of them active and sometimes reaching depths of about 140 m (Fig. 4).

To arrive at appropriate conclusions about available resources and the most suitable areas for quarry development, in addition to the areas where environmental rehabilitation should be done, the studies carried out on this area comprised detailed lithologic and structural mapping with drilling support, and a fracturing survey of all the accessible quarry walls.

5.1. Geologic mapping and structure

The geological studies carried out on the Pardais region were primarily constrained by an almost complete absence of marble outcrops but, on the contrary, there are a lot of large and deep quarries that are true windows to the earth's interior. The geologic mapping of the Pardais region (Fig. 5), which was carried out over 1/2000 scale orthophotomaps, consisted mostly of the geological interpretation of what was observed in the quarry walls. The lithologies identified within the productive unit, which is the Marbles Unit of the Estremoz Volcano sedimentary complex (Fig. 3), are:

- White-coloured and cream-coloured fine- to medium-grain marbles with granoblastic texture. Coloured streaks, greyish, reddish, and brownish, are locally frequent. Thin lenses of metavolcanic rocks are present.
- Grey and dark-grey fine- to medium-grain marbles occurring as metric to decametric discontinuous intercalations within the above unit. A more continuous level marks the top of the productive unit. These are the less valuable ornamental marbles.
- Brecciated marbles associated to NW-SE shear zones, with a thickness ranging from few centimetres to 10 m. These do not have value for ornamental purposes.



Fig. 4. Cochicho—Galvão's large and deep quarry at Pardais area.

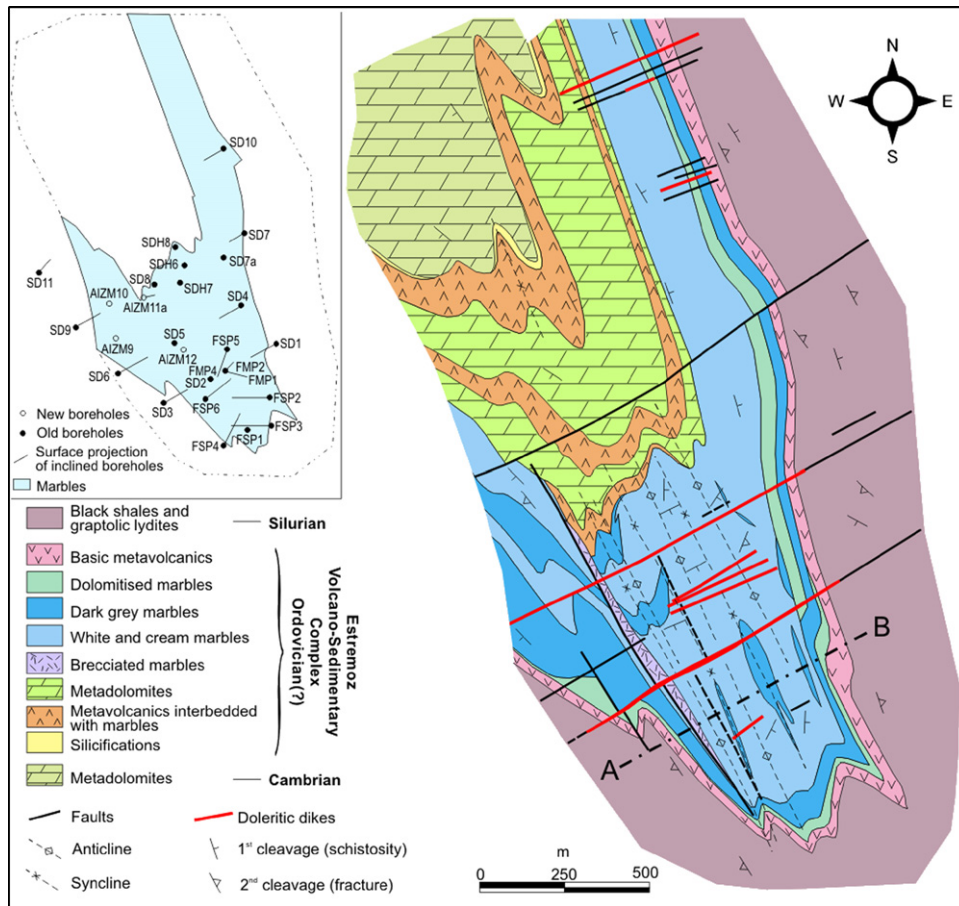


Fig. 5. Geological map of the Pardais region (abridged version of the 1/5.000 map of Henriques et al. [23]), including inset with localisation of the available boreholes.

- Light-brown vuggy dolomitic marbles without any ornamental value. They result from the hydrothermal and/or supergene alteration of the marbles, but this proposal is still under debate as they occur preferentially near the surface along the main discontinuity directions and are also observed in borehole cores at depths as low as 400 m.

A large 15°SE plunging anticline with asymmetric limbs marks the geological structure of the Pardais region (Fig. 6). The marble unit in the SW limb has a thickness of about 200m and dips 45°SW. In the NE limb, it has a thickness of 150 m and is oriented NNW–SSE, dipping 70° ENE. This anticline is cut by transverse faults and altered dolerite dikes and by the above-mentioned longitudinal shear zones. However, at the outcrop scale, many other structural features arise, with emphasis given to minor D1- and D2-folds, and to a more or less dense fracturing network.

As regards economic relevance, most of the quarries are located at the wide hinge zones of cusped anticlines that are parallel to the main structure and where the productive marble unit reaches a thickness of 300 m. However, because of the initial sedimentary lateral and vertical facies

variations, and because of the interference between the two main folding episodes, the economic facies are very difficult to follow along these late second-deformation structures. The associated synclines are tight in shape and often “filled” with dark marbles or top metavolcanic rocks. The cusped morphology seems to be the result of a generalised shearing development along the fold limbs. These usually correspond to the left-lateral NW–SE to NNW–SSE shear zones, which are the barriers to exploitation as they longitudinally limit different marble types.

Due to the scarcity of outcrops, borehole data were fundamental to geologic mapping and its structural interpretation, on the basis of which it was possible to infer abundant marble resources in this region. The most relevant boreholes are represented in the inset of Fig. 5. Those therein referred to as FMP and FSP were drilled for a study on the technical viability of underground exploitation of these marbles [57]. For a very specific cadastral surface area of 6390 m², on the basis of the lithological, structural, and fracturing data of the boreholes, the above-mentioned study proved the existence of 100 000 m³ of underground, economically exploitable marbles at depths of 108.5–124 m below the surface of the earth.

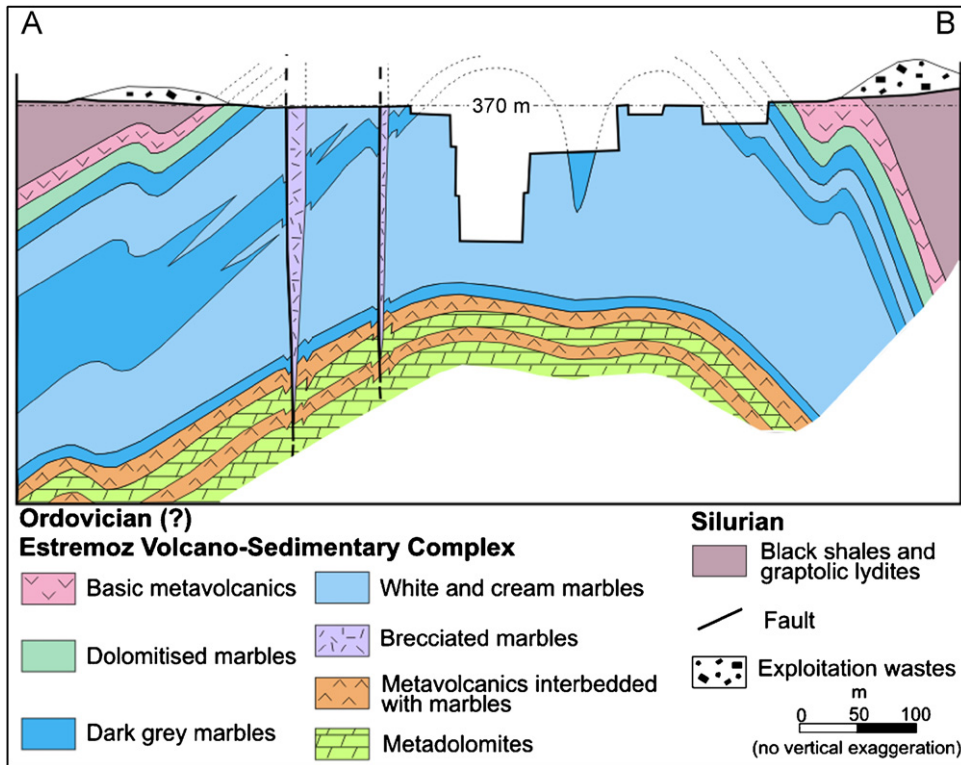


Fig. 6. Geological profile at Pardais between points A and B of the geological map of Fig. 5.

5.2. Fracturing

Fracturing data were obtained by the scan-line method from quarry walls. According to the stereogram in Fig. 7, three main groups of fractures can be outlined for this region. A NNW–SSE oriented group with a near-vertical dip that is aligned with the main regional structures, namely the D2-fold axes, the 2nd cleavage, and the longitudinal left-lateral shears; an ENE–WSW oriented group, also with near-vertical dip that is parallel to the doleritic dikes; and a minor N–S group dipping 45°E. The stereogram also yields some scattered data in the central sector that should correspond to unloading joints.

The data collected about the spacing and continuity of fractures within each directional group are extremely variable [23]. However, its conjoint interpretation with geological mapping led to some main deductions:

- Marble blocks are generically cut with their length parallel to the regional NNW–SSE structural direction, that is, parallel to the 2nd cleavage and to one of the main fracturing direction groups.
- They have a general large-size tendency because fracturing spacings are usually more than 3 m and rarely less than 1 m.
- The initial two fracturing families are more representative and mainly responsible for the size of the marble blocks to be obtained. The first and second fracturing families condition the width and the length of the marble blocks, respectively. The third family conditions

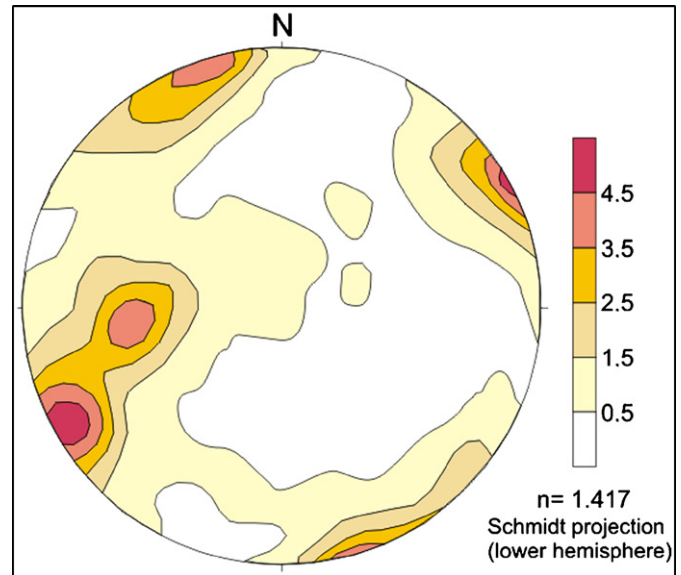


Fig. 7. Stereogram representing the attitude of all the fractures collect at the Pardais region.

both the width and the height, and the near-horizontal unloading joints only determine the height.

- Lower fracturing spacings are verified both near the transversal main faults and dikes, as well as at the structure's NE flank. Therefore, marble blocks tend to be length-penalised near the doleritic dikes and width-penalised at the NE flank.

- As fracturing data were obtained not only near the surface but also deep in the quarries and boreholes, the envisaged fracturing pattern is expected to be found in depth.

The linear density of fractures (ldf) is one of the most important parameters to be analysed when attempting to evaluate the more reliable areas for ornamental-stone exploitation. To have a global picture of the Pardais region with respect to the spatial distribution of the results obtained in each collecting station, especially to assay the extrapolation of those results to the entire study area, a geostatistical approach was implemented according to the methodologies of Luís [27] and Luís and Sousa [28]. After a data normalization of all the 8247 surveyed fractures (1417 by the quarry-scan lines and 6830 from the cores of drill holes), the methodologies involved an assessment of the spatial continuity of the ldf variable. That was carried out through the elaboration of the experimental semivariograms and adjustments to the corresponding theoretical models [26], having in mind the selection of the two main directions of correlation. A spherical behaviour was concluded for the ldf variable, with a low nugget effect and amplitudes of 200 and 80 m for the N60W and N30E directions, respectively. The amplitude assessed for the vertical correlation was 60 m. Finally, the estimation of the spatial distribution of the ldf variable was carried out by ordinary kriging on a net defined by $25 \times 25 \times 80$ m quadrangular prisms, considering all the above-mentioned directional parameters.

The values obtained allowed the elaboration of the map in Fig. 8, which represents the estimated ldf value for each

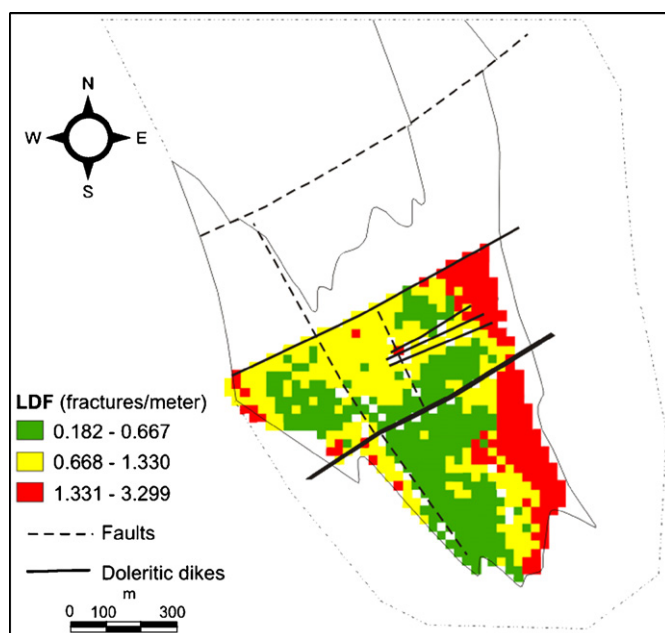


Fig. 8. Linear density of fractures at Pardais area. Estimation of values obtained by ordinary kriging at blocks with length and width equal to 25 m and height equal to 80 m (whose horizontal square sections are represented).

prism. A zonation is clearly distinguished between areas that are more fractured than others, thus having different aptitudes for the ornamental-stone production. The confidence level of these results is globally satisfactory as the procedure includes testing the variation between the estimated results and comparisons with field perceptions about the degree of fracturing in some critical areas. For this purpose, the critical areas are those with sparse and intensively fractured marble outcrops where no data have been collected.

5.3. Resource evaluation

Given the extent of the study area and its large geological complexity, any resource evaluation is meaningful only as a very global approach. By a process of simple geometric calculations based on the acquired geological knowledge, with strong support from the borehole data, it is possible to conclude the availability of about 40 million cubic metres of marble. As the typical yield of the quarries in this region is about 20% of the total amount extracted, the effective volume for economic profit should theoretically be around 8 million cubic metres.

However, there are some rough technical constraints to take advantage of all these resources and carry out successful exploitations because most of the still-available marbles are at great depths. Most probably, only by underground mining can some areas of the deposit be economically reached.

5.4. Geological capability evaluation

To be effective in supporting the industry and the land-use planning decision makers, all the geological data must be integrated in such a way that they can be clearly understandable. To achieve this, the descriptive geological data were subjected to a semiquantitative classification process, on a GIS environment, according to the values presented in Table 3. The lithology, the geologic structure, and the fracturing data are descriptors intended as decision criteria for the definition of the ornamental-stone deposit because they fulfil the data-needs for the prerogatives homogeneity, dimensioning, and fracturing for the study region. At the same time, they also fulfill for this region the data-needs for exploitation.

The lithology descriptor derives directly from the geological map. The geologic structure descriptor, also derived from the geological map, is related to the economic or uneconomic structural targets that were identified during the fieldwork. This classification process allowed, for each one of these descriptors, a cartographic representation of the study area that is the expression of the spatial distribution of the corresponding geological capability (Figs. 9 and 10). As regards the fracturing descriptor, for this region it was considered that the more consistent and strongest fracturing-describing parameter for ornamental-stone purposes is the linear density of fractures. Therefore,

Table 3
Aptitude classification of geological descriptors for ornamental stone production

Descriptor	Aptitude classification	Numeric attribute (<i>n</i>)
Lithology (L)	Without (other lithologies)	0
	Low (marble with abundant streaks, brecciated or dolomitized marble)	1
	Medium (white and cream marble with streaks; grey marble)	2
	High (white and cream marble)	3
Geologic structure (GS)	Not applicable (no marble occurrence)	0
	Low (high-inclined inverted fold flanks; highly deformed marbles)	1
	Medium (normal fold flanks; medium thicknesses; syncline hinges)	2
	High (extensive constant foliation orientation; large thicknesses; anticline hinges; marble at increased depths)	3
Fracturing (F)	Not applicable (no marble occurrence)	0
	Not estimated	1
	Low ($1.33 < ldf \leq 3.30$)	1
	Medium ($0.67 < ldf \leq 1.33$)	2
	High ($0.18 < ldf \leq 0.67$)	3

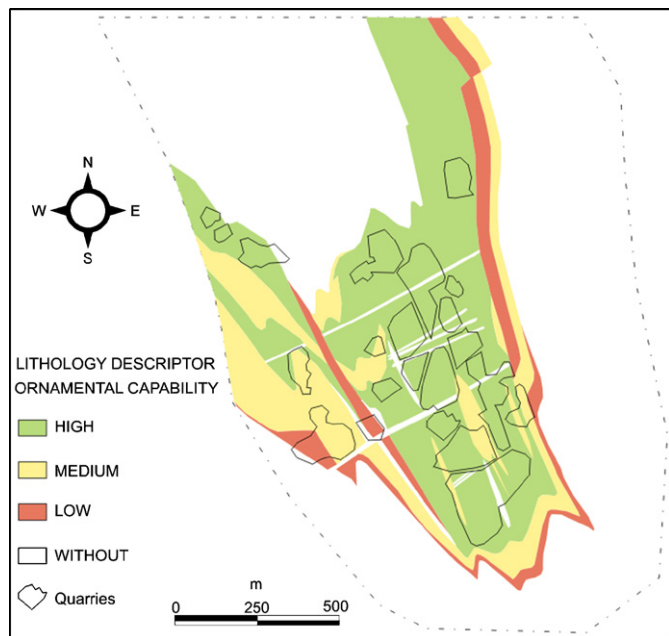


Fig. 9. Ornamental capability of the Pardais region respecting the lithology descriptor.

for this descriptor, the results obtained by the geostatistical distribution of *ldf* were adopted, namely the interval classes defined in Fig. 8. For the areas with marble occurrences but not comprised in the geostatistical estimation process, the

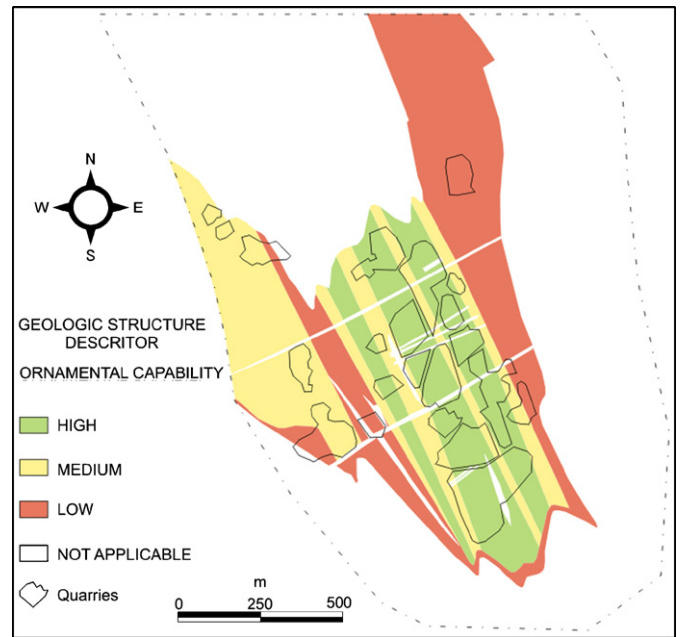


Fig. 10. Ornamental capability of the Pardais region respecting the geological structure descriptor.

worst scenario was considered, that is, marbles with highly fractured surfaces (low aptitude).

As stated earlier, the viability of a rock mass as an ornamental-stone deposit depends on the conjunction of its lithologic, structural and fracturing characteristics. So, to describe the Pardais region according to its capacity for the production of ornamental marbles, these three descriptors were conjointly considered through the expression:

$$GC = \alpha L_n + \beta S_n + \gamma F_n, \quad (1)$$

where *GC* is the geological capability; *L_n*, *S_n*, and *F_n* are the numerical values assigned to the descriptors according to Table 3; and α , β , and γ are the weighing factors.

For the elaboration of the final output presented in Fig. 11, the first step involved the assignment of α , β , and γ weighing factors. Due to the rheological marble properties, the lithologic characteristics are dependent on the deformation processes undergone, and the same is true for the degree of fracturing. Therefore, the lithology and fracturing descriptors are dependent to some extent on the geological structure descriptor. To translate the significance of this descriptor in this region, the following weighing factors were applied: $\alpha = \gamma = 1$, and $\beta = 2$.

The second and final step involved the definition of the interval classes for high, medium, and low geological capability. For this purpose, several simulations were carried out until the results obtained could be verified with some field-picked truths as terms of comparison like quarries abandoned due to high fracturing, or areas with outcrops revealing some specific economic or uneconomic peculiarities regarding the lithology or the geological structure, etc. Here the geologist's field experience about the studied region assumes relevance in distinguishing the

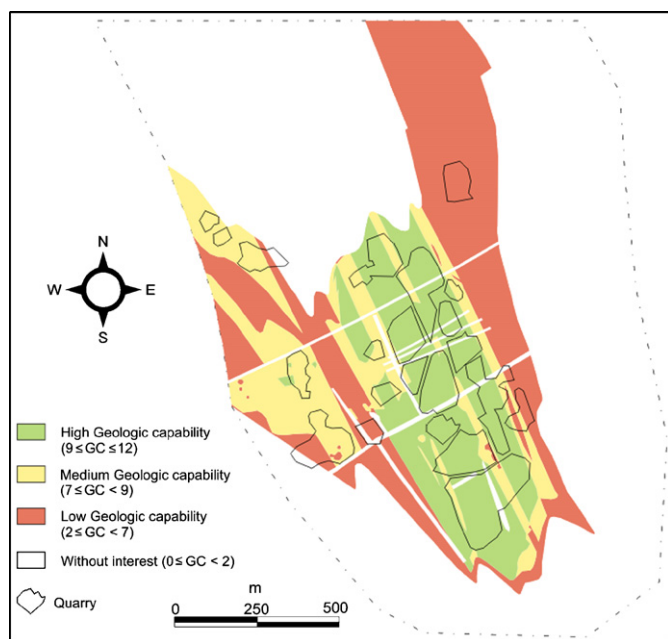


Fig. 11. Ornamental stones geological capability map for the Pardais region.

more critical places for comparison with others that are not so critical due to increased geological uncertainties. If the output obtained is not valid for a critical place, for example, if the output assigns high capability to a restricted area known for high-quality unfractured white marble but in a structural position not favourable to exploitation, then adjustments must be carried out to the interval-class ranges until the output assigns an adequate capability classification to that specific area without compromising the results obtained and validated for other critical areas. From the map presented in Fig. 11, different areas of the Pardais region, with a bigger or smaller aptitude for the production of ornamental stones, can be identified. Medium- to high-geological capability areas are those wherein marble exploitation should take place preferentially. Low capability areas are not suitable for exploitation and existent quarries therein should be considered for environmental rehabilitation. Areas classified as without interest should be considered for other uses (temporary deposition of residues, transformation units, etc.).

6. Discussion

Geologists always have difficulties in giving objective and singular answers to specific problems because their supporting data are subjective as they are the result of individual interpretations of the natural phenomena. The marble-producing area in the Portuguese Estremoz Anticline is a well illustrative example of that situation. The leading question about “Which are the best areas for ornamental-stone production?” gives answers that usually are ambiguous, with plenty of uncertainties, and letting the

arbitrariness of the exploiters and land-use decision makers arrive at the verdict about where to carry out the exploitations.

So as to decrease these situations, the relevant data to be acquired, the geological tools to carry it out, and the processing of these data were emphasised in this study. At least, two main points deserve to be discussed:

- Are the enunciated exploration criteria enough for the objective definition and delimitation of ornamental-stone deposits?
- Is the adopted geological data-treatment procedure effective?

Both questions seem to have positive answers when applied to a productive area in the Estremoz Anticline. A certain volume of rocks at a particular spatial disposition (the dimensioning criterion) can be intended as an ornamental-stone deposit if it allows the obtainment of a significant number of large unfractured blocks with a certain homogeneity degree (texture, colour, etc.). All other logistics-related conditions (distance to consumer centres, access roads, climate, etc.), physical–mechanical properties of the stones (compressive strength, water absorption, etc.), and fashion, are factors external to the deposit itself. They are very important to be considered for exploitability and stone-applicability considerations but only after having a target deposit defined and delimited in space.

Regarding the procedure adopted for the delimitation of the best suitable areas for exploitation, its effectiveness could be verified by the existence of quarries in the study area. As some of them are inactive due to the bad quality of the resources in some places, it was possible to compare the dichotomy “good areas–bad areas” against “good quarries–bad quarries”. The results obtained do have a high degree of subjectiveness because the method is substantiated on a weighing quantification of qualitative geologic data, and therefore it cannot be considered as a sealed procedure. However, it is a methodological one, capable of adaptation to different geological scenarios and different geological-data interpretations. Additionally, it allows singular and understandable answers to the above-mentioned leading question. Further investigation is needed on how to validate the results, in an economically viable manner, when applying the model to areas without an already established extractive industry.

7. Conclusions

In addition to some initial comments intended to bring attention to the economic importance of ornamental stones and to the needs for standardisation in this sector of the extractive industry, this study focused on the setting up of the relevant criteria to be considered for ornamental-stone prospects. They are the dimensioning-related, the homogeneity-related, and the fracturing-related criteria, which can be field-assessed using two main geologic tools: the

lithostructural geologic mapping and the detailed in situ fracturing surveys.

By applying these exploration criteria and tools to a marble productive region in the Estremoz Anticline, the criteria proved sufficient for the efficient definition of economic targets and their spatial delimitation. In the study area, the targets are the wide-hinge zones of the anticline and syncline folds that affect the white-coloured and cream-coloured marbles of the productive unit. The NW–SE stretched limbs of these folds and the transversal NE–SW faults and doleritic dikes are the target-limiting structures.

Considering the needs of the exploiters and the land-use planning decision makers, a GIS-based numerical weighing procedure for the qualitative geologic data was implemented to graphically delimit the best suitable areas for marble production and those for environmental rehabilitation. It proved to be effective as a methodological procedure, capable of being applied to different geological scenarios and/or different geological interpretations.

Acknowledgements

The authors like to thank Marco Meccheri and an anonymous reviewer for their critical and constructive reviews.

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