The Geology as an indispensable tool for optimizing the exploration of dimension stones

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ABSTRACT

Like any Geological Resource, the Dimension Stones can only be exploited where they occur. How they occur is a reflection of geological history that presided over its formation. Their nature determines the mode of deposit and therefore it's potential to be exploited as ornamental stone. The geological setting of the Portuguese marbles became a key factor in the optimization of its exploitation, two ductile deformation phases must be consider, which originates the complex folded metamorphic layering. At least three fracturing systems are responsible for the high segmentation of the marbles in fragile deformation conditions and that must also be considered. Together these geological constraints lead to a really low production ratio (3% - 12%). These low efficiency productions emphasized the emergence of the geological knowledge of individual quarries in order to optimize is exploitation. Until recent years, with high prices for the Portuguese marbles the companies haven't been concerned with the geological knowledge of its quarries, but now that an economic crisis is installed in the sector, basic geological studies in the quarries are mandatory and could save thousands of euros for each company.

Keywords: Marble, Portugal, Structural Control, Estremoz anticline, Marble exploration.

1 INTRODUCTION

Sedimentary, Igneous and Metamorphic rocks have different constraints that define the size of the blocks that will produce. The brittle deformation, which results a regular distribution of fractures, in any kind of rocks, will be a decisive factor when the density of fractures not allow obtaining marketable blocks.

In addition to these tectono-structural fragile constraints, for each type of rock the obtainment of marketable blocks is dependent on more evident factors. For example in sedimentary rocks, the strata thickness, composition and nature of rock and is cement defines whether or not may be used. In igneous rocks will be the state of weathering and the density of decompression joints caused by the massive uplift; in metamorphic rocks, is the existence of slaty plans, open joints and fractures, homogeneity and state of cohesion of the rock massive, etc.

If it's possible to obtain a marketable block (with maximum satisfying dimensions 3mX2mX2m) the state of cohesion of the stone must be such that allow its transformation into slabs for further processing. It is usual to say that any material is good since it have dimension – "Dimension Stone". Other limitations in the use of dimension stone have a lot to do with factors that can be attributing to markets. Thus colors, textures and patterns depend essentially on the tastes of consumers. Companies must present appealing industrial products to highlight some of the nature characteristics of the rock. An orientation to success will be the incorporation in the company of a designer or architect, which means, a professional that beyond knowing in detail the material that sells must also submit application solutions driven by fashion and good taste based on market studies that reflect the tastes consumer.

In this paper the Estremoz anticline geological structure is used as an example of how geological constraints will condition their exploitation for ornamental purposes (Figure 1).

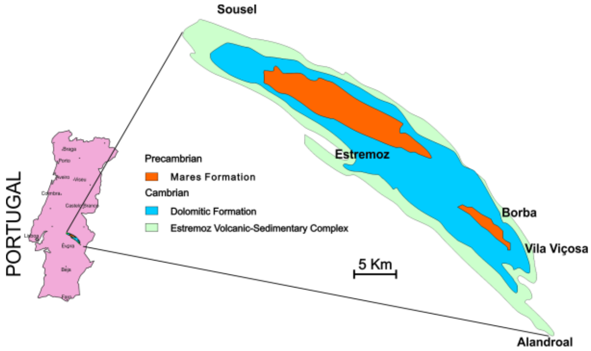

Figure 1. Simplified geology and location of the Estremoz anticline in Portugal.

2 HISTORY

The Estremoz anticline is the main center for Portuguese marble exploitation and one of the most important in the World. A large number of quarries and exploration holes in the area (over 500 considering both) greatly simplifies the access to the marble outcrops and provide unique geological windows, some of which reach some 150 m in depth. The marbles preserve the effects of the Variscan Orogeny and several observed structures in the quarries originate beautiful aesthetic patterns that frequently are emphasized in the final applications of the marbles. Other Paleozoic marbles, which are less relevant, also outcrop in Alentejo region (Vila Verde de Ficalho, Trigaches, Serpa, Viana do Alentejo and Escoural). In every case, the marbles occur integrated in Volcano-Sedimentary Complexes. Although local variations, a similar lithostratigraphic sequence essentially made up of marbles, marble-schist, and intercalations of felsic and basic volcanic rocks is shown. The textural and mineralogical differences between the marbles in these locations are marked by the distinct position that they occupy within the Variscan Orogeny in Portugal (Lopes, 2003).

In the last decades, several exploration studies have been undertaken to valuate this resource (Gonçalves, 1972; Reynaud & Vintém, 1994; IGM, IST & UE, 2000; Vintém, et al., 2003; Carvalho, 2008). Bearing in mind the interaction between mining and the environment, the application of methodologies that allow the proficient land use planning of this area have been studied, which will lead to an efficient global land management (Falé et al., 2004; 2006).

It is well known that these marbles have been quarried since antiquity as a valuable geological resource (Cabral et al., 2001). The oldest evidence of recognition of its use dates back to the year of 370 BC. This archaeological find is represented by a tombstone ordered by the Carthaginian captain Maarbal in their trip from Faro to Elvas and was discovered by investigator Father Espanca in Terena (Alandroal) (Brito da Luz, 2005). Later, in the 1st century of the Roman Period, the structured quarrying in the Estremoz anticline has begun and since that the marbles have been widely used as structural and decorative features of buildings that today are fabulous architectural monuments, e.g. the Roman Temple in Évora, the Roman Theatre in Mérida (Spain), etc. In the middle Ages marbles were used for the construction of palaces, castles and other buildings. From the 15th Century these marbles began to have a more prominent use, both nationally and internationally, having been transported by Portuguese explorers to Africa, India and Brazil. During the next few centuries, these marbles were searched for ornamental purposes and they appear inlaid with various polychromatic associations in several national and international monuments, e.g. Jerónimos Monastery (Portugal), Escorial Monastery (Spain), several monuments in Rome (Italy), Louvre, Notre Dame and Versailles (France). In the 20th century, with the introduction of new exploitation and manufacturing technologies and especially in the 70's with the opening of the Portuguese economy to the exterior, the marble industry took a step forward and since then marble has been exported worldwide. Nevertheless, only in the late decades of the 20th century the marble dimension stone industry of Portugal has achieved an international relevance. In the present, this weight in the international production is decreasing by a number of economic factors that are not the aim of this paper.

The marbles corresponds just to a small part of the Estremoz anticline (Fig. 1). Considering that only 30% of the 27 km2 that the marbles occupy are explored, 10% from exploitation and explorations up to 100m depth, we obtain 220 million tons which, taking into account the maximum average annual exploration of 400.000 tons in the period 2000 - 2002 period (INE – Instituto Nacional de Estatística), allows pointing reserves for about 550 years. This value is calculated by default because that the deposit can reach over 400m in Fonte de Moura – Pardais (Vila Viçosa), and between Carrascal and Encostinha (Borba), where the finest marbles and of better quality are more than 280m depth. So the knowledge of the geological setting of the marbles became a key factor in the optimization of the extractive industry. The calculated reserves of marbles in the Estremoz anticline structure indicates that the exploitation possibly will last for about 500 years, considering a depth exploitation of 100 meters (today that value has only already been achieved in a dozen of quarries) and a peak of production that has occurred in 1995.

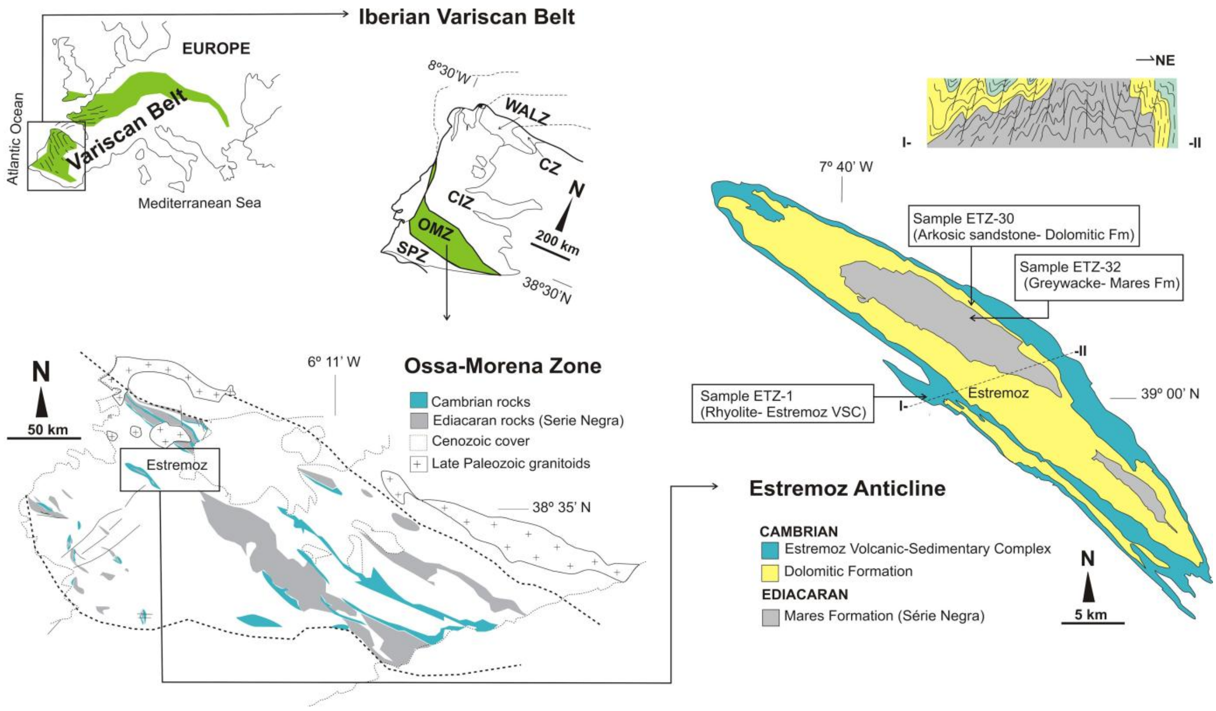

Figure 2. Location of the Estremoz anticline in the Iberian Variscan Orogenic Belt. On the lower left corner the precise locattion of the samples that allow the precise dating of the Estremoz stratigraphic sequence. Adapted from Pereira et al., 2012.

3 GEOLOGICAL SETTING

The Estremoz Anticline is a major NW – SE oriented structure Variscan structure of the Ossa-Morena Zone in Portugal that extends for 45 km, from Sousel to Alandroal, with a maximum width of 10 km. (Figures 1 and 2), is situated in the "Sector of Estremoz-Barrancos" of the Ossa-Morena Zone, Portugal (Oliveira et al., 1991). The geological lithostratigraphic sequence comprises units since the Upper Precambrian to the Devonian (Piçarra, 2000).

The marbles with ornamental interest are placed over the "Dolomític Formation", of Lower Cambrian age (Carvalhosa et al., 1987, Pereira el al, 2012)), which always contact through a siliceous level that in all the structure, defining a geologic cartographic level guide, are also dated Upper Cambrian (Pereira et al 2012) and can reach the Upper Ordovician as the most probable age for the Estremoz marble (work in progress, Lopes, 2003).

In detail, the pre-Silurian stratigraphic sequence of the Estremoz Anticline includes (Gonçalves, 1972; Gonçalves and Coelho, 1974; Gonçalves and Oliveira, 1986; Oliveira et al., 1991; Lopes, 2003): (1) Ediacaran greywackes, shales and black cherts (Mares Formation- Série Negra Succession), which crop out in two separate elongated ribbons in the core of the Estremoz Anticline; (2) Cambrian arkosic sandstones at the base (which unconformably overlie the Série Negra rocks), and dolomitic limestones (~400 m) towards the top (Dolomitic Formation); (3) a silica-rich (quartz and iron-rich) layer atop the dolomitic limestones; (4) thick-bedded Cambrian–Ordovician (?) limestones (70–100 m) with interbedded basalts, rhyolites and shales (Volcanic–Sedimentary Complex of Estremoz, which includes the Estremoz marbles); The geochemistry of basalts and rhyolites indicates a within-plate environment, probably related to rifting processes (Mata and Munhá, 1985).

The stratigraphic sequence of the Estremoz Anticline (Figure 3) was deformed and metamorphosed under greenschist metamorphic conditions during the Variscan (also known as Hercinian) orogeny (Carboniferous). Variscan deformation and metamorphism in the Ossa-Morena Zone was responsible for the development of 110°-170°-trending folds and ductile and brittle–ductile shear zones under greenschist metamorphic conditions. So, the macrostructure results from the interference two Variscan folding phases of wrenching (Lopes, 2003). D1 folds are associated with development of extensional shear zones and *boudinage*. Mylonitic foliation and stretching lineation parallel to the maximum elongation direction (170–180°) and shear criteria (asymmetrical tails of porphyroclasts, C–S planes) are consistent with movement with top-to-the-North. The Estremoz Anticline is characterized by 110–130° striking tight to close D2 folds with vergence to the NE. D2 folding is associated with slaty cleavage and discrete brittle-ductile shear zones along the reverse and stretched limbs of tight folds. These shear zones strike 110–130° and have a gently (b10°) NW- or SE-plunging mineral lineation parallel to D2 fold axis (Lopes, 2003, Pereira et al., 2012).

As pointed, in the Estremoz anticline two deformation mechanisms – shortening perpendicular to axial plans (pure shear), and longitudinal distinguishing flow (simple shear) – interact. From that results antiform and more frequent peculiar sinform folds with parallel limbs (similar) with relatively ample hinges and more or less flattened limbs (Figure 4).

The heterogeneous nature of this deformation is extended in virtue of the regional left lateral shear component that occurs concomitantly with the

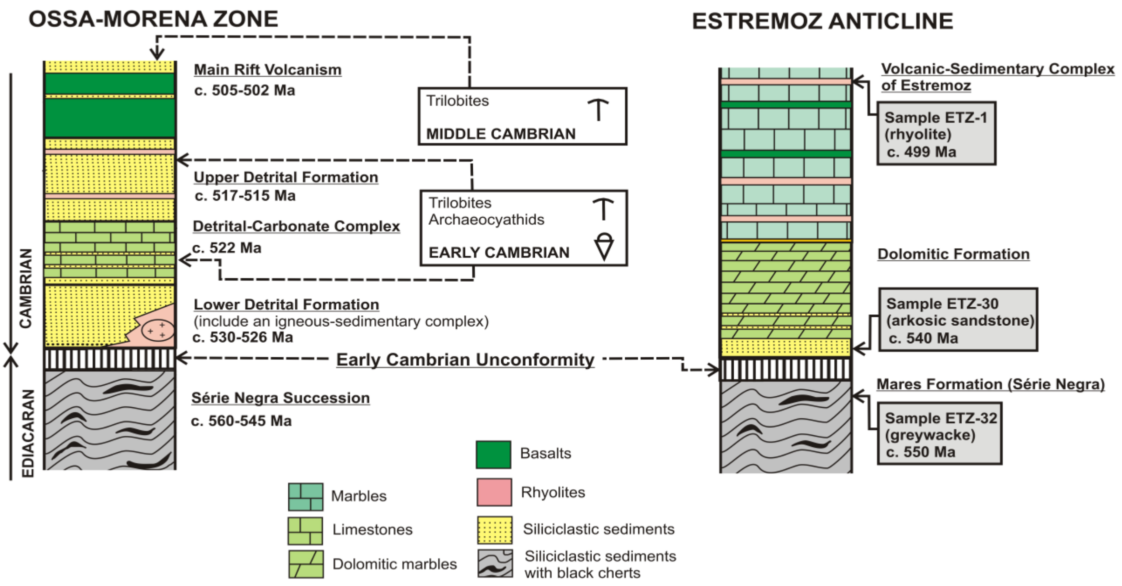

Figure 3. Correlation between the stratigraphic scales of the Ossa - Morena Zone and the most recently presented to the Estremoz anticline. Adapted from Pereira et al., 2012.

flattening. This description configures the tangential transpression (Araújo, 1995), with transport for the quadrant north or the northwest, cinematically similar to the described model as left transcurrent, that estimates a diachronic succession of transpression and transtension events, for the Variscan orogeny in the Ossa – Morena Zone in the region (Silva, 1997).

The continuing transpressive deformation regimen, from D1 to D2, led to the development of left lateral deformation NNW-SSE, sub-vertical shear zones. Progressively the deformation regimen varies since essentially ductile to a fragile one, originating structures that vary from folds to tectonic breccia's, all the intermediate stages can be found in the quarries, and in the end this characteristics also induce the consequent separation into compartments of the anticline, sometimes with drastic economic consequences; a quarry could simply close because the marble ends along these tectonics frontier.

A simple model could be present (Figure 5) to clarify some aspects; effectively the figure shows a segmentation with a regular disposal of WSW – ENE, vertical accidents and the NNW – SSE, northeast verging shear zones, in the reality such regular distribution does not occur, the figure only intends to captivate the attention for the orientation and occurrence of these discontinuities. Segmentation WSW - ENE coincides with the occurrence of dolerite dykes, installed in release tension fracture planes WSW-ENE, sub-perpendiculars to the axial plan of the macrostructure defined for the second phase of folding (D2) (Figures 4 and 5). The space and relative importance between these discontinuities are changeable. Greater spaces will be of the order of the hundreds of meters and the minors are spaced between 50 cm (or less) and 1 m. There is also a good relation between the width of the vertical dykes that had installed in these cracks and the respective spacing. In the SE periclinal termination of the anticline a vertical *en échelon* disposal is observed in the dolerite dykes, indicating a vertical movement deeping of the SE block.

marble, which always has economic consequences.

Figure 4. Opened fold with streched vertical limbs. The “M” pattern of the mesoscopic folds indicates a medium position in relation to the macrostructure. Quarry ABV (António Bento Vermelho), Fonte da Moura, Pardais.

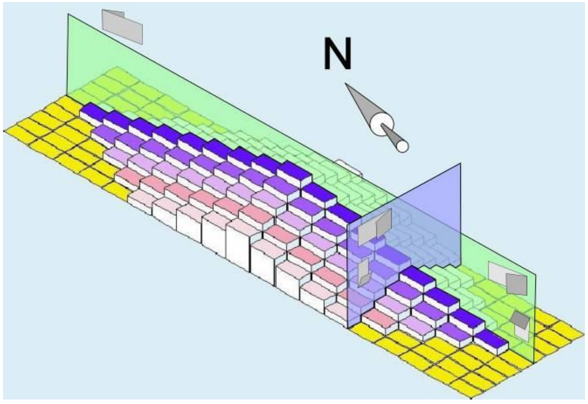

Figure 5 - Schematic and extremely simplified representation of the longitudinal and transversal segmentation of the anticline of Estremoz. Although simplicity, this model represents a good correlation with what it is observed in the quarries that, frequent are limited by faults associeted to doleritc dykes (ENE-WSW) and shear zones (NNW-SSE).

This longitudinal, NNW-SSE, correspond to the segmentation direction of the reactivation in fragile – ductile regimen of previously developed shear bands. Its localization is controlled for the vertical limbs of the second phase folds. Thus, the greater spacing corresponds to the wave length of these folds and is of the order of the hundreds of meters or a little less. The greater spacing of WSW – ENE discontinuities are one order of magnitude inferior to the previous NNW-SSE discontinuities.

The graphical transposition of these spacing for directly reflects in abnormal and little natural character regularly of the segmentation of the structure schematized there, whose naïf nature already was reported. In some of these NNW – SSE accidents occurs the recrystallization sin and after kinematics of the marble, for what, these structural discontinuities not always are expressed in lithological discontinuities, with the exception that exists variation in the variety of the marble, which always has economic consequences.

Chronologically the WSE – ENE discontinuities are posterior to the NNW – SSE shear bands and are expressed for left horizontal movements in most cases difficult to quantify. The coalescence of these two families of discontinuities is responsible for a segmentation of the structure block-type where, at least at the surface, the marble presents proper texture characteristics (different varieties). The correlation between this segmentation and the layering related by Pereira (1981) is a task that is for completing and certainly it will contribute for better knowledge of the distribution of the different types of marbles in the structure, from where economic values will be achieved.

Finally the late Variscan and Alpine fields of tension, act in the Estremoz anticline. The fracturing induced by lithostatic decompression associated with the one caused by the quarrying activities is also present and many times can be identified. Regarding the brittle deformation variables involved in the conditioning of the fracturing of marbles in the Estremoz anticline, they are such that the regional values shown in Table 1 must solely be taken as reference. Therefore, local conditions (to the level of the quarry) that go to determine which families of fractures are present, must be carefully investigated in order to give geological engineers valuable information for the correct planning of the marble quarrying.

4 CONCLUSIONS

Having into account the general geologic characteristics of the Estremoz anticline can concluded that in terms of economic feasibility of the marble explorations as ornamental stones, the geologic constraints play a basic role. This became each day more important since is getting more difficult to access to the good quality raw material, so the need to develop more expensive underground quarrying of the marbles (Figure 6).

Since that are so many geological constraints one of the most important conclusion is that isn't possible to apply the regional geological characteristics of the region as a general model in one given quarry. Each case is different and a local study must be guided by the following points:

1. Lithology;
2. Ductile deformation of the marbles (folds);
3. Occurrence of Shear Bands and Dolerite Dykes as majors frontiers controlling the varieties of marble that may be present in a quarry;
4. Deformation in half – ductile and in fragile conditions of marbles (faults, fractures and joints). Enhancing the i) Segmentation NNW-SSE; ii) Segmentation ENE-WSE, and iii) late Variscan fracturing discontinuities arrays;
5. Microscopic petrography characterization with the purpose to determine qualitatively or semi-quantitatively the deformation rate of the marble and if it is possible, inferring on the proximity of not explicit zones of shear through petrographic fabric analysis;
6. Finally in the particular case of the Estremoz anticline, when the quarries are small, wherever possible should be study the possibility of joint adjacent explorations in a coordinated plan of action, reducing costs and allows deeper mining in health and security work conditions.

Table 1 – Main families of fractures in the anticline of Estremoz, after data collected in Lopes (2003), Reynaud and Vintém (1994) and Ladeira (1981).

FAMILIES	STRIKE	DIP
NW - SE (associate the imperfections of left movement)	N5° - 10°W N5° - 10°W N30° - 45°W (longitudinal to the structure) N40° - 45°W N40° - 45°W N70° - 75°W	45° - 50° NE 70° - 75°NE Subvertical 45° - 50°NE 35° - 45°SW Subvertical
NNE - SSW (associate the delayed dolomitization)	N5° - 10°E (diagonal to the structure) N40°W to N45°W	Subvertical Subvertical
ENE - WSW (associates the dolerite dykes)	N60° - 75°E (transversal to the structure)	Subvertical
Sub-horizontal plane	ENE - WSW NNE - SSW	≤30° ≤30°

Figure 6. Underground quarry in the SW limb of the Estremoz anticline. The best quality marble pursuit requires a good geological knowledge of the deposit and only then becomes profitable underground mining of this resource. Lugramar Company Quarry.

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