Global Heritage Stone: Towards International Recognition of Building and Ornamental Stones

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Global Heritage Stone: Estremoz Marbles, Portugal

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Abstract: Paleozoic calcitic marbles are found in the Estremoz Anticline, Ossa-Morena Zone (Southern Branch of the European Variscides in Portugal). This 40 km NW–SE structure presents outcrop continuity and intense mining activity since the Roman Period. The structure has a Precambrian core and the younger rocks are from the Devonian Period. The marbles occupy an intermediate stratigraphic position in the Cambrian age Volcano Sedimentary Sequence. The Variscan Orogeny had two pulses with different intensities under ductile and brittle tension fields. The Alpine Cycle also caused more fracturing of the marbles. The geological features imprinted in the marbles are beautiful aesthetic patterns highlighted when used as dimension stone.

Since the Roman period, pieces of art made with Estremoz Marble were exported abroad and can be found in museums and archaeological sites throughout Europe and North Africa countries. Present day, Estremoz Marble objects can be found all over the world.

The very rich marble based heritage is omnipresent in cities, and the countryside is marked by intense mining activity side by side with rural industries; therefore the region has unique characteristics allowing the development of integrated industrial tourism routes, promoting sustainable development of industrial, scientific and technological cultural opportunities.

The historical and widespread application of these marbles in national and international monuments, some of them already part of the UNESCO World Heritage Sites, is a condition to propose them as Global Heritage Stone Resource for their international recognition.

Constituting a symbol of economic strength, good taste and distinction, it can be said that, virtually, there is no city in Portugal where Estremoz Marble has not, somehow, been used in both small works of art or utilitarian objects as public monuments and in private homes. It is estimated there would be hundreds of thousands of buildings that have used Estremoz Marble. Historically documented, usage dates back to the fourth century BC (Alarcão & Tavares 1989; Maciel & Coutinho 1990; Cabral *et al.* 1992) and extends to where currently, owing to the global commercial trade, Estremoz Marble can be found all over the World.

On the Sistema de Informação para o Património Arquitectónio (SIPA) webpage (Information System for Architectural Heritage, which is a system of information and documentation of Portuguese architectural, urban and landscape heritage of Portuguese origin managed by the Institute for Housing and Urban Renewal (IP – IHRU), http://www.monumentos.pt), 179 national monuments are referenced where Estremoz Marble has been used. By itself, this fact constitutes an indicator of the marble's importance in the history of Portugal and certifies its value as a Global Heritage Stone Resource to be preserved. This long-term intense use is a sign of its high quality, the only way to justify the demand that has continued for more than 25 centuries; otherwise, demand would have ceased. Nowadays business associations and Portuguese dimension stone companies have made a huge effort towards the promotion and marketing that has led to the creation of the brand 'Stone PT' (http://stone-pt.com/en/). In addition to other marbles, this brand also includes other Portuguese dimension stones. High levels of quality, certification, verification and management are associated with this brand. In fact, besides the Estremoz Marble, Portugal has mining units of ornamental rocks throughout its territory (i.e. Carvalho *et al.* 2013 for more detailed information). The northern part of the country is rich in igneous rocks, particularly granites, while Jurassic microcrystalline limestones are concentrated in the Maciço Calcário Estremenho (central western part of the country). With huge relevance during in the 15th–18th centuries in the Portuguese maritime expansion and the rebuilding of Lisbon after the 1755 earthquake, some varieties of Cretaceous 'Lioz' limestone were exploited near Sintra (Pêro Pinheiro, Negrais, Montemor, Lameiras) north of Lisbon. Nowadays there are a few quarries in these limestones. There are also considerable reserves of Jurassic limestone breccias in Algarve (S. Brás de Alportel – Tavira, South Portugal), as well as a kind of Cretaceous nepheline syenite, unique in the world, exploited in Serra de Monchique

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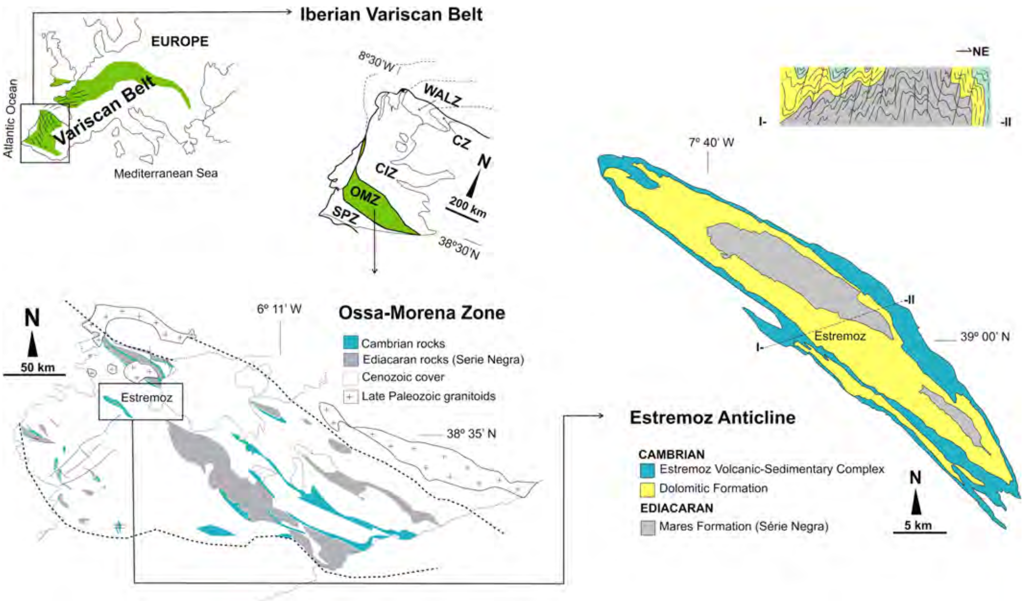

Fig. 1. Location of the Estremoz Anticline in the Southern Branch of Iberia Variscides. The map of Iberia with major tectono-stratigraphic zones is adapted from Julivert 1987, *in* Pereira *et al.* 2012. The simplified geological map is adapted from Gonçalves 1972. On the top left there is a diagramatic cross section of the Estremoz Anticline adapted from Pereira *et al.* 2012.

(Algarve, South Portugal). Carboniferous and Ordovician slates (schists) have an extractive pole of considerable dimension in the Oporto-Valongo-Arouca region and in the northeast part of the country (Trás-os-Montes). Additional exploitation of Ordovician slates also occurs in Barrancos, Alentejo. To highlight the excellent quality of Valongo shales, they are mostly destined to exportation and the manufacture of English billiard tables.

With the exception of a small marble occurrence in Vimioso (Trás-os-Montes, Northeast Portugal) and calcitic skarns related to the Late Cretaceous Sintra granite intrusion (near Lisbon), both lightly exploited in the past, all the Portuguese marble

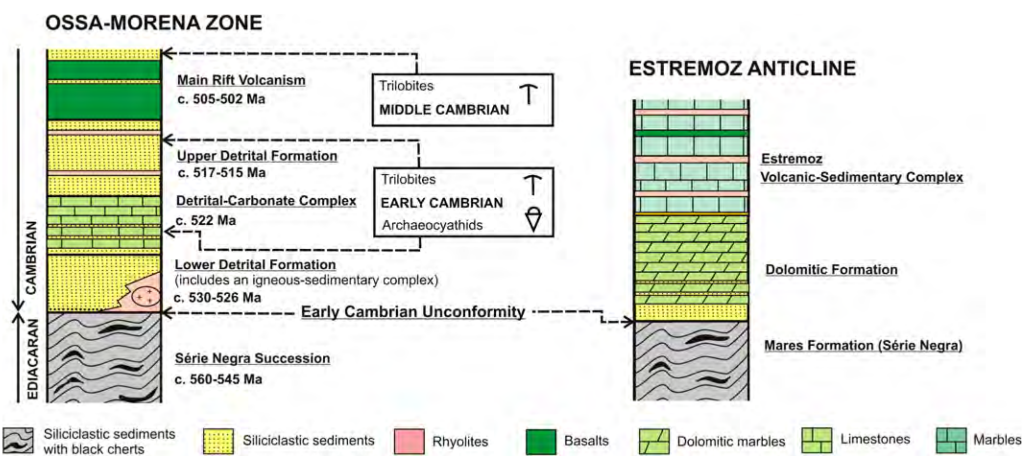

Fig. 2. Stratigraphy of the Ossa-Morena Zone and the Estremoz Anticline. The geochronological ages represent new data for the Estremoz Anticline (Adapted from Pereira *et al.* 2012, after Gonçalves 1972 and Sánchez-García *et al.* 2010).

dimension stone production comes from Alentejo. This region also has considerable reserves of late–post Variscan pink, white and grey granites and dark diorites (from the north to the south there are active quarries in: Alpalhão, Monforte-Santa Eulália, Vimieiro-Pavia, Évora and Reguengos de Monsaraz).

The dimension stone industry in Portugal exports limestones, granites, slates and marbles to 126 countries. Portugal is the eighth country in the World Dimension Stone trademark, second considering *per capita* rate. The 2012 business value was 1400 million euros comprising 3300 companies and directly employing 24 000 workers. Nevertheless, 92% of foreigner stone clients only recognize one type of Portuguese stone; the pink marble from Estremoz.

According to information obtained from Directorate General of Energy and Geology (www.dgeg.pt), the 2013 dimension stone production in Portugal was 2 527 168 tons, with a market value of € 140 206 000. In the same year, the 27 km^2 area (Moreira & Vintém 1997) of marbles covering the Estremoz Anticline produced a value of € 25 110 000 (169 558 t), corresponding to 6.7% of the national volume of production and 17.9% of the value. This information reveals that a relatively small area produces one fifth of what is produced throughout the country, reflecting the rarity of such ornamental rock and hence, the relatively high economic value of the region.

In fact, the marble outcrops correspond just to a small part of the Estremoz Anticline. No more than 30% of the 27 km^2 that the marble occupies

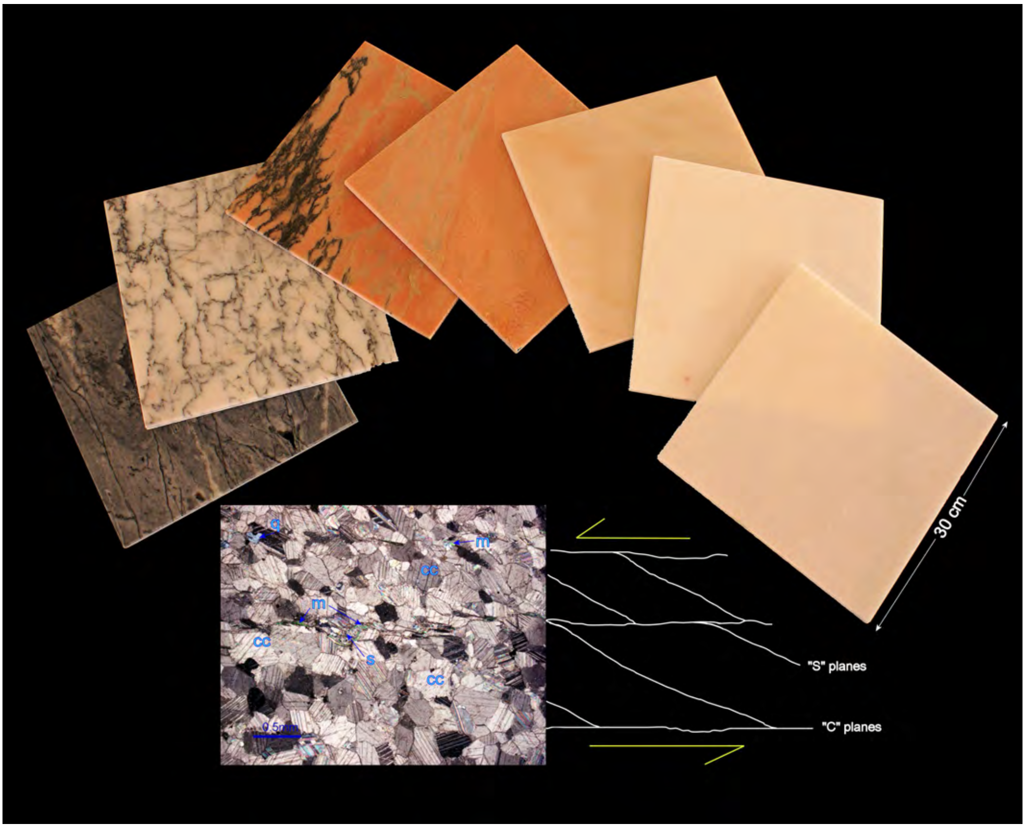

Fig. 3. Some of the most well known varieties of Portuguese Estremoz Marbles. From the left to the right they include: ‘Ruivina da Lagoa’ (Ruivina from Lagoa); ‘Pele de Tigre de Pardais’ (Tiger skin from Pardais); ‘Rosa Vergado de Borba’ (Pink with stripes from Borba); ‘Rosa Aurora’ (Pink Dawn); ‘Creme de Pardais’ (Cream from Pardais); ‘Branco Rosado de Estremoz’ (White pink from Estremoz) and ‘Branco Vigária’ (Vigária White). The ‘Rosa Vergado de Borba’ shows the close relation between the green layers of non-carbonate minerals and the presence of pink colour in the stone. The image at the bottom represents a thin section obtained cutting the ‘Branco Rosado de Estremoz’ marble along the stretching lineation and perpendicular to the foliation defined by the ‘C’ planes. The ‘C’/‘S’ interpretation structure of the stone is represented in the sketch on the right. Minerals: cc, calcite; m, moscovite; s, sericite and q, quartz.

are exploited. Considering 100 m as the maximum depth of exploitation and 400 000 tons as the average annual exploration (INE, Instituto Nacional de Estatística) with a recovery rate of 10%, it can be estimated that 220 million tons of marble reserves exists, enough for more than 500 years of continuous marble quarrying. This value is calculated by default because the drills showed that often the marbles layers can reach over 400 m (i.e. Fonte de Moura-Pardais and Vigária in Vila Viçosa county and Carrascal and Encostinha in Borba county).

Geology

As already stated, Alentejo's Paleozoic calcitic marbles are found in a dozen locations from Elvas to Vila Verde de Ficalho (south central Portugal), all belonging to geological Ossa-Morena Zone units (southern branch of the European Variscides in Portugal) and having similar stratigraphic sequences but different grades of metamorphism. In the past, all these outcrops were exploited, but nowadays only the Estremoz Anticline has active quarries; about forty (there were 260 in 1987, although these used to have substantially lower dimensions).

The Estremoz Anticline (Gonçalves 1972) is a 45 km NW–SE structure with a maximum 10 km width in the vicinity of Estremoz (Fig. 1) that presents outcrop continuity from Sousel in the north to Alandroal in the south.

First described by Silva & Camarinhas (1957), the stratigraphic sequence of the Estremoz Anticline includes (Gonçalves 1972; Gonçalves & Coelho 1974; Gonçalves & Oliveira 1986; Oliveira *et al.* 1991; Lopes 2003, 2007; Pereira *et al.* 2012) (Fig. 2):

(1) Precambrian Ediacaran greywackes, shales and black cherts (Mares Formation, Série Negra succession), which crop out in two separate elongated NW–SE trending 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 thick) towards the top (Dolomitic Formation);
(3) A 50–5 m-thick silica-rich layer atop the dolomitic limestones (quartz and iron-rich, pyrite at depth, which is transformed into iron oxide pseudomorph crystals at the surface). The intersection of this layer was the criterion used to stop the drilling carried out in past projects to define the thickness of the marble (Lopes 2003);
(4) Thick-bedded Cambrian–Ordovician (?) limestones (originally 70–100 m thick) with interbedded basalts, rhyolites and shales (this succession is known as the Volcanic–Sedimentary Complex of Estremoz, which includes the Estremoz Marbles with ornamental interest). The shales, black shales and black cherts, younger rocks aged Silurian–Devonian (Piçarra 2000; Lopes 2003, 2007), surround the Estremoz Anticline.

Caused by regional tectonic processes, overlapping by faults and thickening of the marble layers by folding along hinge zones, the marbles can reach over 400 m thick.

The geochemistry of the interbedded basalts and rhyolites indicates a within-plate environment, probably related to lower Paleozoic rifting processes (Mata & Munhá 1985).

The stratigraphic sequence of the Estremoz Anticline was deformed and metamorphosed under green-schist to lower-amphibolite metamorphic conditions during the Variscan Orogeny (Carboniferous). Variscan deformation and metamorphism in the Ossa-Morena Zone was responsible for the development of 110°–170°-trending folds and ductile to brittle–ductile shear zones (Lopes 2003; Pereira *et al.* 2012).

The Estremoz Anticline resulted from the interference of two Variscan folding phases of wrenching. 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, Fig. 3) 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

Table 1. *Chemical composition of Estremoz marbles, adapted from Casal Moura* et al. *(2007)*

Parameter	Mean ± Standard deviation (%) $n = 36$ samples	Max. (%)	Min. (%)
SiO_2	1.54 ± 1.01	4.67	0.12
AI2O_3	0.61 ± 0.37	1.69	0.10
Fe_2O_3	0.15 ± 0.07	0.31	0.04
MnO	0.01 ± 0.01	0.04	0.01
CaO	53.85 ± 0.97	55.55	51.65
MgO	0.57 ± 0.50	2.76	0.04
Na_2O	0.14 ± 0.31	1.80	0.03
K_20	0.18 ± 0.14	0.82	0.04
TiO_2	0.01 ± 0.01	0.01	0.00
Loss on Ignition (LOI)	42.90 ± 0.58	43.49	41.32

Table 2. *Mineralogical composition of Estremoz marbles, adapted from Casal Moura* et al. *(2007)*

Mineral	%	Observations (36 samples)
Calcite	90–100	27 samples >99%
Dolomite	0–10	Detect in 6 samples
Quartz	0–2	Detect in 34 samples
Muscovite/ Sericite	<1	Detect in 14 samples
Biotite	Vest.	Detect in 2 samples
Felspars	Vest.	Detect in 2 samples
Turmaline	Vest.	Detect in 1 samples
Opaque minerals	<1	Detect in 3 samples

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 (<10°) NW- or SE-plunging mineral lineation parallel to the D2 fold axis (Lopes 2003, 2007; Pereira *et al.* 2012).

The tardi Variscan fragile deformation is also presented in two sets of arrays. The first is closely related with the D2 folds and consists of sub-vertical NNE–SSW and ENE–WSW trending conjugate faults, frequently associated with NE–SW, subvertical tension cracks. The second fault set is characterized by sub-vertical NNW–SSE and NE–SW trending faults. Acting together and having associated exploitation tension release fracturing, all of these fractures cause a high density of discontinuities that results in a lower rate of the marble exploitation (in some cases 3.5%).

Frequently the more developed ENE–WSW left lateral faults are filled with Triassic dolerite.

The NNW–SSE shear zones, associated with the stretched limbs of the D2 folds together with the dolerite filled ENE–WSW discontinuities, define sub-rectangular boundary array domains that can limit the quarries. In each of these domains, at surface, the marbles exhibit characteristic colours, patterns, hues and textures well known in the industry. More than 40 commercial names used by the industry reveals this variety.

Discrete and less frequent left-lateral NNE–SSW faults and conjugate right-lateral NNW–SSE faults, both vertical, which intersect all previous structures, can be related with the expression of the Alpine Orogeny in the region and cause more fracturing of the marble.

Recent studies based on U–Pb geochronology of detrital-inherited and igneous zircons from sedimentary and igneous rocks of the Ossa-Morena Zone have reinforced the understanding that SW Iberia reflects the geodynamic evolution of the North-Gondwana margin during the late Ediacaran to early Cambrian time (Chichorro *et al.* 2008; Linnemann *et al.* 2008; Pereira *et al.* 2008, 2011, 2012; Sánchez-García *et al.* 2008, 2010; Solá *et al.* 2008). Similar study in the Estremoz Anticline defined the ages of the main units in this major Variscan structure of the Ossa-Morena Zone (Pereira *et al.* 2012). A Precambrian age was confirmed in a core (greywacke of the Mares Formation–Serie Negra Succession; Late Neoproterozoic), and newly formed zircons in a rhyolite bed from the volcano–sedimentary complex of Estremoz date the calcitic marble sequence (only exploited as dimension stone) as Late Cambrian (Fig. 2). Because the upper structural control of the dated layers is ambiguous, the calcitic marbles can be slightly younger (Lower Ordovician) and hence have the same age as the Vermont Danby marbles (EUA) (Ratcliffe *et al.* 2011; Doolan 1996; Baldwin 1982). The geodynamic implications of this hypothesis need more data to be supported.

The C, O and Sr stable isotope studies, together with mineralogical, petrographic, chemical and

Table 3. *Chemical chromophores elements in some Estremoz marbles, according to Gomes da Silva (1989)*

Element	Atomic number (Z)	COMMERCIAL MARBLE NAME				
		Branco Vigária (White) ppm	Rosa Carrascal (Pink) ppm	Creme Vigária (Cream) ppm	Ruivina Escuro (Dark blue) ppm	Ruivina Raiado (Light blue) ppm
Ti	22	117	393	127	197	255
V	23	6.0	7.9	6.6	7.8	12.5
Cr	24	4.5	14.0	11.0	8.0	22.3
Mn	25	68	88	61	81	17
Fe	26	350	1330	350	420	840
Co	27	–	–	–	–	–
Ni	28	3.6	7.2	2.6	3.9	5.7
Cu	29	6.6	5.1	7.2	8.0	8.01
Zn	30	21.4	23.2	19.6	23.3	22.5

Fig. 4. This picture shows an example of geometric patterns obtained by polishing the Ruivina (dark blue to grey colour marble variety) marble slabs in open book.

micro textural analysis, proved to be a very robust ensemble of methods to determine the provenience of the marble used in antiquity (Cabral *et al.* 1992; Taelman *et al* 2013). In particular the $^{87}Sr/^{86}Sr$ isotope ratios of the Estremoz Marble compared with other Iberian and the main Mediterranean marbles shows distinguishing values and hence allows determination of the geological origin, even when there is a very small amount of material to study, as is the case with pieces of art. The average isotopic ratio for the Portuguese marbles is 0.708655 (range between 0.708502 and 0.708919). These values are consistently lower than those obtained for other non-Paleozoic marbles of the Iberian Peninsula and higher than those found in other Mediterranean marbles (Taelman *et al.* 2013).

The distinguishing criteria from other Paleozoic Alentejo calcitic marbles, which inferred reserves are much less relevant (Vila Verde de Ficalho, Trigaches, Serpa, Viana do Alentejo and Escoural), are

Fig. 5. Another example of geometric patterns obtained by polishing the slabs in open book. The original stone was a ‘simple striped’ pink Borba marble.

Table 4. *Physical properties and carbonate composition of Portuguese and foreign marbles**

Type	Localization	Compression Breaking Load kg/cm^2	Compression Breaking Load after Freezing Test kg/cm^2	Bending Strength kg/cm^2	Volumetric Weight kg/m^3	Water Absorption at N.P. Conditions %	Apparent Porosity %	Thermal Linear Expansion Coefficient 10^{-6} per °C	Abrasion Test mm	Impact test: minimum fall height cm	Carbonate Composition
		EN 1926	EN 12371	EN 12372	EN 1936	EN 13755	EN 1936	EN 14581	EN 14157	EN 14158	
Portuguese Marbles											
Branco Estatuária	Vila Viçosa, Pardais, Lagoa	788	895	208	2709	0.08	0.23	9.9	2.8	65–70	98% Calcite 54% CaO 43% CO_2
Branco	Vila Viçosa, Bencatel, Vigária	967	933	208	2713	0.07	0.17	12.6	2.1	45–50	99% Calcite 55% CaO 44% CO_2
Branco Rosado	Estremoz, Sta. Maria, Cerca de Sto. António	970	950	243	2718	0.07	0.20	7.3	2.0	50	94% Calcite 55% CaO 44% CO_2
Crème Venado	Borba, S. Tiago de Rio de Moinhos, Herdade do Mouro	990	863	238	2713	0.05	0.15	11.1	2.6	60	99% Calcite 54% CaO 43% CO_2
Rosa Aurora	Vila Viçosa, Bencatel, Santos	872	950	179	2717	0.06	0.16	7.3	3.7	50–55	99%Calcite 54% CaO 43% CO_2
Ruivina Escuro	Borba, S. Tiago de Rio de Moinhos, Ruivina	930	952	270	2715	0.05	0.14	5.4	2.6	45–50	99% Calcite 55% CaO 43% CO_2
Ruivina da Fonte da Moura	Vila Viçosa, Pardais, Fonte da Moura	863	977	256	2703	0.10	0.28	14.8	2.0	55	95% Calcite 54% CaO 43% CO_2
Worldwide Marbles											
Afyon Tiger Skin	Turkey	648	447	65	2710	0.1	0.2		6.66		99.6% CaO
Afyon White	Turkey	701	590	151	2730	0.1	0.2		0.51		95.2% CaO
Bianco Carrara Unito C	Italy	1209	1181	174	2688	1.6		7.2	4.72	73.8	55% CaO 44% CO_2
Calacatta Bianco	Italy	844	959		2674	1.5		10.3		71	
Greek Cipolino	Greece	965		155	2705	0.11			8.55		57% CaO 43% CO_2
Imperial Pink	Brazil	1199	1182	184	2732	0.06	0.17	8	3.31	46	96% Calcite
Mystique Dark	China	833		83.8	2693	0.08					
Salome	Turkey	1019	1019	174	2730	0.1	0.4		0.37		78.9% CaO
Thassos Saliara Snow White vein	Greece	971		185	2880	0.68			0.35		45.9% CO_2 33.8% CaO 19.9% MgO
Villa Grey	China	898		75.6	2820	0.17					

*Adapted from: Ministério da Indústria e Energia, Direção Geral de Geologia e Minas (1992, http://www.dgge.pt/); http://rop.ineti.pt/rop/images/intro/intr_en.php and http://www.stoneexpozone.com/. Analytical procedures in accordance with the standards (EN) mentioned and described in the accessed font sites on March 3, 2014.

Fig. 6. Images of marble processing plants near Vila Viçosa. (**a**) Partial view of a polishing slab line. (**b**) Details of polished slab at the end of the line. (**c**) Slabs ready to export. (**d**) Tiles with several dimensions and marble varieties packed to export overseas. Photos were taken in the following companies: Plácido José Simões S.A.; Criamármore – Mármores de Portugal Lda.; ETMA – Empresa Transformadora de Mármores do Alentejo, S.A. and Empresa Marbrito, Indústrias Reunidas de Mármores, Lda.

Fig. 7. In the beginning of 2014, the deepest quarry in the Estremoz Anticline was 150 m deep. It is located in the SE periclinal termination of the structure and belongs to F. J. Cochicho Lda. and Cochicho, Lda. companies.

Fig. 8. This image shows the only operating underground marble quarry in the Estremoz Anticline. It is located in the southwest limb of the structure, near Vila Viçosa, and belongs to Lugramar – Sociedade Lusitana de Mármores, Lda company.

based in mineralogical and textural characteristics. The Estremoz Anticline sequence is also correlated with the one found in the Zafra-Alconera region (Spain), it can be easily distinguished by its finer grain texture and it also has archaeocytes-bearing beds at the bottom and trilobite bearing beds at the top (Lopes 2003).

In every case, these Paleozoic marbles occur integrated in volcano-sedimentary complexes. Although there are local variations, a similar lithostratigraphic sequence essentially made up of dolomitic marbles, marble schist, and calcitic marbles with intercalations of both felsic and basic volcanic rocks is shown. The textural and mineralogical differences between the marbles in these locations are marked by the distinct position they occupy within the Variscan Orogeny in Portugal (Lopes 2003).

Fig. 9. Activities during the VIII Challenge Trophy in a quarry located in the southwest limb of the Estremoz Anticline, Vila Viçosa.

Geochemistry and mineralogy

The calcitic marbles exploited as dimension stone in the Estremoz Anticline are characterized by a very high content of calcium carbonate, often more than 99%, and very low contents of other minerals. Tables 1 and 2 show chemical and mineralogical composition determined in 36 samples of the most representative varieties of exploited Estremoz Marble.

Marble colours

Marble colours always raise some curiosity. The major elements of chemical composition of the

Fig. 10. Evidence of Roman Estremoz marble applications. (**a** & **b**) *In situ* wedges and groove marks of quarrying activity (Marbrito Lda. Quarry, Lagoa, Vila Viçosa). (**c**) Marble block with two unfinished sarcophagi accidentally found in 1965 during the exploitation works of the company António Matias Rocha & Irmãos in Pardais, Vila Viçosa, now in exhibition in the Vila Viçosa's Archeology Museum. (**d**) Marble tubs milled with characteristic dissolution marks caused by weak acid olive oil, private collection. (**e** & **f**) Pieces found in the nineteen sixties (Herdade da Vigária, South of Vila Viçosa) and offered by the Solubema S.A. company to the Vila Viçosa's Archeology Museum. (**e**) Unfinished block where a column was being carved. (**f**) Low relief representing an aquatic deity, found near a ravine in marble with water flowing.

Fig. 11. The Roman Temple of Évora (Portugal) has rich Corinthian capitols of marble topping granite columns, whose bases are also made of white Estremoz marbles (Lopes *et al.* 2013). On the right can be seen the Cathedral of Évora cupola.

marbles exhibit no differences to justify different colours, and therefore some trace chemical elements, called chromophores, can be a clue for the marble colouration differences. These elements belong to the fourth row of the Periodic Table, specifically to the subgroup B (Ti, V, Cr, Mn, Fe, Co, Ni, Cu and Zn). Gomes da Silva (1989) first attempted to relate these trace elements with the colours displayed by the marbles (Table 3). Apart from the pink marble, which has higher levels of Ti, Mn and Fe, there are no significant differences among the others. In fact, there is close relationship between pink marbles and the levels of rich muscovite-, sericite- and quartz-bearing green layers. The thicker the layer, the pinker the marble is. Away from these layers, the marble gently loses the pinkish colour and becomes white or cream (Fig. 3). The grey and bluish darker shades are due to the presence of organic matter, which sometimes occurs concentrated in layers sub-parallel to the regional second-phase foliation.

Dimension stone characteristics

The excellence of the marble of Alentejo makes it very versatile, allowing its use on decks, coverings of the interior and exterior (outdoors and indoors) and for interior decoration (fireplaces, floors, tables, staircases, kitchen countertops, etc.).

It is also often used in urban furniture such as benches, garden tables and fountains, in funerary art, as masonry in engineering works, as structural elements in buildings and for paving of sidewalks and roads.

Its workability and variety of colours makes it the first choice of stones for sculptors who, throughout the ages, have produced artworks of great refinement and high aesthetic value.

The high quality of Estremoz Marble, fine to medium grained, excellent mechanical-physical properties, as well as aesthetic beauty (which is attested to by the prices they fetch and also by the large volumes of rock quarried), places Portugal at the forefront of world marble production. Colours vary from white, cream, pink, grey to black and streaks with hues in any combination of these colours are possible (e.g. white with pink streaks). The types of pink marble are internationally coveted because of their quality and beauty (Fig. 3). Locally, high-quality white or cream-coloured blocks are also used in statue manufacturing.

As was stated before, the marble reflects the effects of the Variscan Orogeny and several structures preserved in the quarries originate aesthetic patterns that frequently are emphasized in the final applications of the marbles (Figs 4 & 5).

Analysing the values related to physical properties and carbonated composition of various Portuguese marbles and some from Turkey, Italy, Greece, China and Brazil (Table 4), it appears that Portuguese marbles from Estremoz–Borba–Vila Viçosa present values perfectly framed by the values revealed by other marbles. Regarding the compression breaking load before and after freezing, the values are relatively similar, with the

Fig. 12. The marble has been primarily used as a decorative element; however there are also many examples of utilization as building structural elements. The examples shown are: The Renaissance Paço Ducal (ducal palace) of Vila Viçosa; Monsaraz pillory; detail of Montemor-o-Novo pillory; Estremoz Castle Tower; columns in the Estremoźs

exception of the values presented by the 'Bianco Carrara Unito C' from Italy, 'Imperial Pink' from Brazil and 'Salome' from Turkey with very high values for these kind of dimension stone. For values of bending strength, the Portuguese marbles exhibit very favorable results.

The remaining parameters have values expected for carbonate rocks with Portuguese marble possessing optimal characteristics for interior and exterior applications, funerary art and the creation of furniture.

Glimpse of the Estremoz marble industry

Marble exploitation runs mainly in open pit, well-deep quarries with right vertical steps, with or without a ramp for bottom access. Only one underground mine is still active and can be visited by tourists with a professional tour guide assessment.

It is a modern industry that mainly uses highly specific Portuguese and Italian dimension stone exploitation and manufacturing technology (Fig. 6). A large number of quarries in the area greatly simplify direct access to the marble and provide unique geological windows, some 150 m in depth (Figs 7 & 8).

In the last decades, several exploration studies have been undertaken to evaluate 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 proficient land use planning of this area have been studied, which will lead to an efficient global land management (Falé *et al.* 2006).

Land planning and other activities in the Estremoz Marble Region

The intense mining activity strongly dynamizes the economies of the regions where it develops; inevitably mischaracterize the environment, transforming it in most cases permanently. When the activity ceases or slows down, it is essential to find solutions for its reactivation in any possible business, taking into account the sustainability of these regions. Until the end of 2010, the Estremoz Anticline was part of the studies carried on in the Project Rumys, 'Rutas Minerales de Iberoamérica y Ordenamiento Territorial: un Factor Integral para el Desarrollo Sostenible de la Sociedad', developed by CYTED (Cooperação 'Ciencia y Tecnología de la Región Iberoamericana'), covering aspects as diverse as geology, mining, tourism, historical patrimony, gastronomy and society. On each route, the project compiled an historical inventory of the production and enhancement of cultural heritage and geomining, showing its relationship with society. Two books (Falé *et al.* 2008, 2009) and two papers (Lopes & Martins 2010; Lopes *et al.* 2013) published the results of that inventory and predicted the social impact expected, in order to promote regional development. This work was continued by the Turismo de Portugal, I.P., the INALENTEJO–QREN funded project 'Promotion of Tourism Industry'. From the beginning there was commitment from the University of Évora (responsible for the scientific content), municipalities of Sousel, Estremoz, Borba, Vila Viçosa and Alandroal and several marble companies that support the project in the field. Resulting from that, the brand 'Rota Tons de Mármore' (Route Shades of Marble) was proposed and implemented and can be enjoyed by tourists (http://www.rotatonsdemarmore.com/pt) at different timespans with differentlevels of knowledge, by following one of their proposed programs or specifying a personalized program according to their interests. These routes, located in the Estremoz Anticline, promote the tourism industry, which necessarily includes the simultaneous and integrated development of various aspects such as tourism, scientific, industrial, cultural and sporting activities.

The region has unique conditions and astonishing scenarios for the practice of adventurous tourism and the hosting of radical sport competitions ('offroad' events, 'Trial Bike', 'Motor Trial', etc.). The first edition of the Challenge Trophy two-day event happened in May 2010 in the counties of Sousel, Estremoz, Borba, Vila Viçosa and Alandroal, and counted one hundred athletes. The participants had to realize several orienteering and obstacle competitions, taking advantage of the fact that some quarries (with interrupted mining works) present technical and safety conditions for its realization (Fig. 9).

Certain quarries have high quality acoustic conditions allowing the realization of cultural events. The Portuguese Armada Band concert in a quarry, performed during the Global Stone Congress 2012, was a success. After this, different styles of

Fig. 12. (*Continued*) Church of Santa Maria; Bible support in the Cathedral of Évora, and detail of the Jerónimos (or Hieronymite) Monastery in Lisbon showing Estremoz marble applications in the high altar and paintings depicting scenes from the Passion of Christ and the Adoration of the Magi by the artist Lourenço de Salzedo (1572–1574). The Hieronymite Monastery was declared a National Monument in 1907 and in 1983 UNESCO classified it as a 'World Heritage Site'.

performing arts shows have been hosted (theater, dance, fado, rock, Alentejo's Folk Songs ('*Cantares Alentejanos*'), folk groups and classical music), showing the versatility of the 'Natural Stages' offered by the abandoned marble quarries.

Therefore, the inoperative quarries near the urban centres can be reconverted as art and leisure destinations. This can be done with low funding projects, involving some superficial modelling, planting screening trees, building of infrastructures and adaptation of the land for appropriate use and security. In fact this is already a reality in the new Marble Museum of Vila Viçosa.

The Estremoz Marble as Heritage Stone

The artistic, architectural, monumental and cultural heritage based on the marble is so extensive that its inventory in this work would not be possible. The description of such a library is partially already done in 'SIPA' (http://www.monumentos.pt/) and Portuguese municipal archives. It can be said that pieces of art, sites and monuments with some historical significance and scientific or cultural value are properly recorded in those inventories, which are starting points for more detailed studies. Even more important, most of them are free to access and are accessible online.

Thus, in order to demonstrate the real value of Estremoz Marble as Heritage Stone, some examples will be chronologically presented. Any visit to the villages of the 'Marble Triangle', or nearby Évora, reveal how prevalent these examples are. Hundreds of examples can easily be found without any search effort. Moreover, in any Portuguese city, it is possible to find application examples of this 'noble stone'.

It is well known that these marbles have been quarried since antiquity as a valuable geological resource. The oldest evidence of recognition of its use dates back to the year 370 BC. This archaeological find is represented by a tombstone ordered by the Carthaginian captain Maarbal in his trip from Faro to Elvas and was discovered by the investigator Father Espanca in Terena (Alandroal) (Brito da Luz 2005).

Many traces of Roman marble quarrying were found in last century's exploitation works. Some of these were lost by neglect and lack of recognition of their historic value. Nevertheless, it was still possible to gather pieces that attest to the intense activity in the Roman Period. These pieces (columns, unfinished sculptures, or pieces damaged during the process of sculpting sarcophagi, structural elements for buildings, tanks to preserve meat and fish, etc.) belong to private owners but also can be observed in the Archeology Museum, in Vila Viçosa, National Archaeological Museum (Lisbon) and Museu Monográfico de Conímbriga (Condeixa-a-Nova, Coimbra), among others. I just left a place with '*in situ*' evidence of Roman marble quarrying that will be preserved and integrated into tourist historic routes. (Fig. 10).

Maciel (1998) argues that the number of found objects, their diversity and variation in manufacturing processes over time, reveals a progressive development of the extraction of marble with its zenith in Late Antiquity, in the third and fourth centuries. This activity will also be related to the rise of Emerita Augusta (now Mérida) from a regional capital to become the capital of the province *Diocesis Hispaniarum*. All roads are renewed and the use of the marble of Estremoz is done not only in major cities as in *Villae*, which are all over the Alentejo: Nª Srª da Tourega, Nossa Senhora de Aires, Santa Vitória do Ameixial, Silveirona, Torre de Palma, among many other places (Carneiro 2011). In fact, in the Roman Period, the Estremoz Marble was widely used for structural and decorative features of buildings that today are fabulous architectural monuments, for example the Roman Temple in Évora ((Fig. 11), the Roman Theatre in Mérida (Spain) and the Roman Towns of Ammaia (Taelman *et al.* 2013) and Volubillis, Morocco, where the 'Portuguese pink, a palepink marble exploited by the Romans near Vila Viçosa in the Lusitania which, till now, has not yet been identified outside Iberia' (Antonelli *et al.* 2009).

Between the 15th and 18th centuries, Portugal enjoyed a period of great prosperity. The essence of all of this heritage was constructed in the cities and towns. They combine religious and military heritage with civil architecture, erudite or formal and vernacular, a perspective that provides for stimulating excursions on foot along the oldest and most agreeable streets in the historical centres. The styles succeed each other – Gothic, Renaissance, Mannerist, Baroque, Neoclassical – as in other European countries. In Portugal there occurred an original style that is called Manueline. Although the name comes directly from King Manuel (1495–1521), a fortunate monarch in whose reign India was reached and Brazil was discovered, this style preceded him and continued after his death. It has its roots in the late Gothic and, in Alentejo, has also tasted something of the Mudejar style, giving rise to the curious examples called Manueline-Mudejar. In its final phase, it existed alongside Renaissance and Mannerist styles (http://www.visitalentejo.pt/en/). All these styles used marble for the construction of palaces, churches, 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

Fig. 13. White Estremoz marble applied on a staircase of a private home in Borba.

to Africa, India and Brazil. During the next few centuries, they were sought for ornamental purposes and appeared inlaid with various polychromatic associations in several national and international monuments, for example, Cathedral of Évora and Geronimo's Monastery (Portugal), Escorial Monastery (Spain), several monuments in Rome (Italy), Louvre and Versailles (France) (Casal Moura *et al.* 2007). In the 20th century, with the introduction of new exploitation and manufacturing technologies and especially in the 1970s 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 (Brilha *et al.* 2005).

As was pointed out, the marble is not just for carving. Its application as a raw material for construction has also been done for millennia, since early man discovered the potential of this noble material. The art of giving more value to the marble, or other types of dimension stones, requires more than just technical training. Sensitivity is needed

Fig. 14. Detail of 'Filho do Sol', a sculpture in 'Rosa Portugal' marble by César Valério, Vila Viçosa, Portugal, completed on May 11, 2013. Complementary information is at http://www.cesarvalerio.net and http://www.cesarvalerio.com/.

from the extraction step through all the stages included in the processing until the proper application of work (Figs 12 & 13). Only then can the exceptional beauty of the raw material be taken advantage of, otherwise the final result could be disastrous both from a technical standpoint, as well as from an aesthetic point of view.

The marble has life and it is temperamental, changing colour and texture with the daylight, humidity and weather. It also ages! Its diversity makes it unique and can show truly abstract paintings. Their traces show up a winding convoluted and strong personality, imposing itself to the eyes of the beholder. The diversity of colours makes it irreverent. Nevertheless, it is being presented constant, reflecting the constancy of its colour appearance, determined by the conditions that prevailed in its genesis.

Those who work the marble, first have to know it well and become familiar with it. Only then will they be able to shape it wisely. It is not easy to tame a rebellious nature, but there are those who have done it so masterfully, like Michelangelo and Bernini, among other geniuses of the sculpture. Armed with art and skills they possessed the ability to give life to stone. Also today there are wonderful sculptors but they have technology to help facilitate their work (Fig. 14).

Conclusions

The Estremoz Marble is among the purest carbonate rocks exploited as dimension stone (more than 99% $CaCO_3$), also has excellent physical properties and can be used both indoors and outdoors in virtually all climates and latitudes. In fact, since the fourth century BC, there is a written record of its continuous use in works of art and monuments.

This paper also points out that a lot of the marble taken for granted as Italian was actually quarried in Portugal. Only more studies, in ambiguous cases, can tell how real this statement is. Currently, the data obtained by very precise analytical techniques can remove doubts as to the provenance of the marbles used in certain monuments or works of art. These analyses require only a few grams of sample rock, which can be easily obtained without damaging the works of art and monuments.

The originality of the stone material exploited in the Estremoz Anticline and the continuous use of it for twenty five centuries as part of the Portuguese and world history in the construction of historical monuments, as well as in the production of many objects and sculptures, determined that research about the Estremoz Marbles would focus on the description and application of this Heritage Stone material. This work will help the international knowledge and recognition of Portuguese marbles as natural stone that are part of our heritage.

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