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Artículo

Ancient Quarries on the Estremoz Anticline (Ossa Morena Zone, Portugal): Exploitation, Use and Dispersion of Estremoz Marbles during Roman times

Canteras históricas del Anticlinal de Estremoz (Zona de Ossa Morena, Portugal): Explotación, Uso y Dispersión del Mármol de Estremoz durante la Época Romana

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Abstract: The use of crystalline marbles from Estremoz Anticline, Alentejo (Southern Portugal), and their historical exploitation are documented since the Roman period. While most of the ancient quarries in the area were originally discovered due to the intense mining activity of the 20th century, the remains that still preserved *in situ* are very scarce, as this recent exploitation has often erased the existing evidence. However, in several of the cases here documented, recent quarrying operations have contrastingly provided and helped preserve these traces of earlier extractive activity. The analysis of aerial photographs, confirmed by a field visit to the area, identifies almost five hundred marble quarrying and exploration sites in the Estremoz Anticline, most of which were opened in the 70s and 90s of the 20th century, while official records show that in the late 80s there were 187 quarries operating simultaneously around the villages of Estremoz, Vila Viçosa and Borba.

Today, for various reasons (including the globalisation of the economic market, the ageing of the population, recurring economic crises, the recent tightening of safety regulations, etc.), only around 40 quarries are still active, some of which are over 150 metres deep. Nevertheless, the analysis and conservation of the archaeological evidence of exploration remains a significant challenge. This paper presents a summary and characterisation of the identified ancient quarries and remains in terms of their location, geological setting and marble type, but also of the ancient exploitation methods observed. It also explains the current challenges for the conservation of the relevant geodiversity found and some resulting geoconservation measures, defined according to the site, which could be implemented on a larger scale to conserve and display the unique architectural and cultural heritage of these sites. This study assumes a particular relevance so that both landowners and industry continue to support and preserve this historical and cultural, tangible and intangible heritage of undeniable and differentiating value for this raw material.

Keywords: Historical quarries; Estremoz Marble; Roman Period; cultural heritage; Ossa-Morena Zone

Key points:

The marbles of the Estremoz Anticline have been exploited since Roman times.

The modern industry of marble as an ornamental stone has threatened the preservation of the archaeological artifacts and ancient quarries.

For the sake of future memory and because marble has an intangible heritage value, the existing mining heritage should be protected, enhanced and promoted.

Resumen: El uso de mármoles cristalinos del Anticlinal de Estremoz, Alentejo (Centro Sur, Portugal), y su explotación histórica, está documentado desde la época romana. Aunque la mayoría de los descubrimientos de canteras antiguas en la zona se debieron originalmente a la intensa actividad extractiva del siglo XX, los restos que aún se conservan *in situ* son muy escasos, ya que la explotación reciente a menudo borró estas evidencias de canteras antiguas. Sin embargo, en varios casos documentados aquí, los trabajos recientes en las canteras proporcionaron y conservaron estas huellas de la actividad extractiva anterior. El análisis de imágenes aéreas, confirmado por la visita sobre el terreno, identifica casi quinientos yacimientos de extracción y exploración de mármol en la zona del Anticlinal de Estremoz, la mayoría de ellos abiertos en las décadas de los 70 a los 90 del siglo XX, mientras que los registros oficiales muestran hasta 187 canteras explotadas simultáneamente en torno a los pueblos de Estremoz, Vila Viçosa y Borba a finales de la década de 1980. Hoy, por diversas razones (entre ellas la globalización del mercado económico, el envejecimiento demográfico, las repetidas crisis económicas, el reciente refuerzo de la normativa de seguridad, etc.), sólo siguen activas unas 40 canteras, algunas de las cuales alcanzan más de 150 metros de profundidad. Sin embargo, el análisis y la conservación de las pruebas de exploración arqueológica siguen siendo un reto importante. Este artículo presenta un resumen y una caracterización de las canteras y restos antiguos debidamente identificados en lo que respecta a su ubicación, entorno geológico y tipo de mármol, así como a los métodos de explotación antiguos observados. También explica los retos actuales para conservar la geodiversidad relevante encontrada y algunas medidas de geoconservación resultantes que se definieron según el yacimiento y que podrían aplicarse a mayor escala para conservar y mostrar el patrimonio arquitectónico y cultural único de estos yacimientos. Este estudio es relevante para que los propietarios de los terrenos y los exploradores continúen apoyando y preservando este patrimonio histórico y cultural, tangible e intangible, de innegable y diferenciador valor para esta materia prima.

Palabras clave: Canteras históricas; Mármol de Estremoz; Época Romana; patrimonio cultural; Zona de Ossa-Morena.

Puntos clave:

Los mármoles del Anticlinal de Estremoz han sido explotados desde la época romana.

La industria moderna del mármol como piedra ornamental ha amenazado la conservación de artefactos arqueológicos y una cantera historica.

Por el bien de la memoria futura y porque el mármol tiene un valor patrimonial inmaterial, el legado minero existente debe protegerse, valorizarse y promoverse.

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Supplementary information ↓

1. INTRODUCTION

The use of stone for building purposes can be traced back several millennia. From a relatively early stage, humans also revealed a particular interest in some stones which, due to their appearance and physical properties, were mostly employed with an aesthetic purpose. Though the earlier records for sculptural and architectural decorative stone use can be found in the Early Dynastic period and the ancient Egyptians have often been considered the precursors of the ornamental stone extraction industry (Harrell, 2014). The most significant development of the use of dimension stones as structural, architectonic and sculptural stone occurred during the first millennium BC, increasing their use as a conspicuous element in the art and architecture of the Greek world and then significantly intensified and expanded during the Hellenistic period, as the *diádochoi* monarchies stemmed increasingly elaborate schemes of architecture and sculpture (Karaglou, 2016). Indeed, the use of different coloured natural stones for architectural decoration in this period is attested, for instance, in the description of Cleopatra's palace provided by Lucan (Phars. X, 110 – 126). This period also witnessed the eastward expansion of the Roman Republic, from the conquest of Greece in 146 BC to the fall of Ptolemaic Egypt after *Actium*. The increasing Hellenic acculturation of the Roman society, as noted by Horace (Epistulae, II, 156 – 157), led to the improvement of the use of ornamental stones, enhancing the use of different, often coloured, stone materials for decorative purposes, which is one of the most recognisable features of the Roman world. As most of these stones did not occur locally and required a given effort to supply and work, their usage has often been considered an index of wealth and social status.

Whereas in the eastern Mediterranean, there was a long tradition in ornamental stone exploitation and use, the picture was strikingly distinct from the West. Although some evidence suggests the occasional use of marble in earlier periods, it was only with the transformations that occurred under the government of Octavian that the ornamental stone started being exploited and used extensively and systematically on western decorative architectural and sculptural features. From this period onwards, there was an extensive trading network that could supply a wide range of lithotypes across the Mediterranean basin (Russell, 2013) and a considerable investment in surveying and exploiting stone that occurred locally, as it happened in *Hispania* province. Indeed, the demand derived from the considerable urban development observed during this period and the inherent construction of large public buildings required large quantities of material, leading to the survey and exploitation of local resources (Fusco & Mañas, 2006; Mañas & Fusco, 2008).

The integration of the Roman provinces, applying the models of the capital of the Roman Empire, also led to the use of marble in public monuments, namely temples, theatres and bathhouses, decorating them with sculptures, capitals and entablatures in the same material. Although they transported the raw or already worked marble blocks all over the Empire, the pragmatic sense of the Romans led them to look for local sources that could supply the good-quality ornamental rocks (Justino & Coutinho, 1990).

In this context, the area corresponding to the Roman province of *Lusitania* (i.e., most of present-day Portugal and part of the Extremadura region in Spain) was particularly relevant, once this region contains

several occurrences of good-quality stone, notably marbles, which were exploited from the first half of the 1st century AD and widely diffused on a regional and supraregional scale. In the Lusitanian province, the capital *Augusta Emerita*, and other cities such as *Pax Iulia* (Beja), *Myrtilis* (Mértola), *Ebora* (Évora), *Olisipo* (Lisbon) or *Conimbriga* (Coimbra) took part intensely in exploration and exploitation in this province.

Perhaps the most important of these marble occurrences is the Estremoz Anticline (Fig. 1), a geological regional structure extending up around 42 km on an NW-SE regional trend along the areas of the present-day Sousel, Estremoz, Borba, Vila Viçosa and Alandroal municipalities, in the Alentejo region (Portugal). Quarrying of the Estremoz Anticline should have begun shortly after the creation of the *Lusitania* province and it has been frequently assumed that the exploitation of the Estremoz Marbles (general name used for all the marbles exploited in the Estremoz Anticline; e.g., Lopes & Martins, 2015; Moreira & Lopes, 2019) could have been rather intensive during all the Roman period, because the white and veined marbles from this region (but also the pink and grey ones) can be found in several architectural and sculptural elements disseminated over a large area (see last section; Moreira *et al*., 2020 and Moreira, 2022 for a review). The need for rocky raw material for monumentalisation of the main urban centres led to a search for sources of supply to build and decorate large public complexes (Fusco & Mañas, 2006).

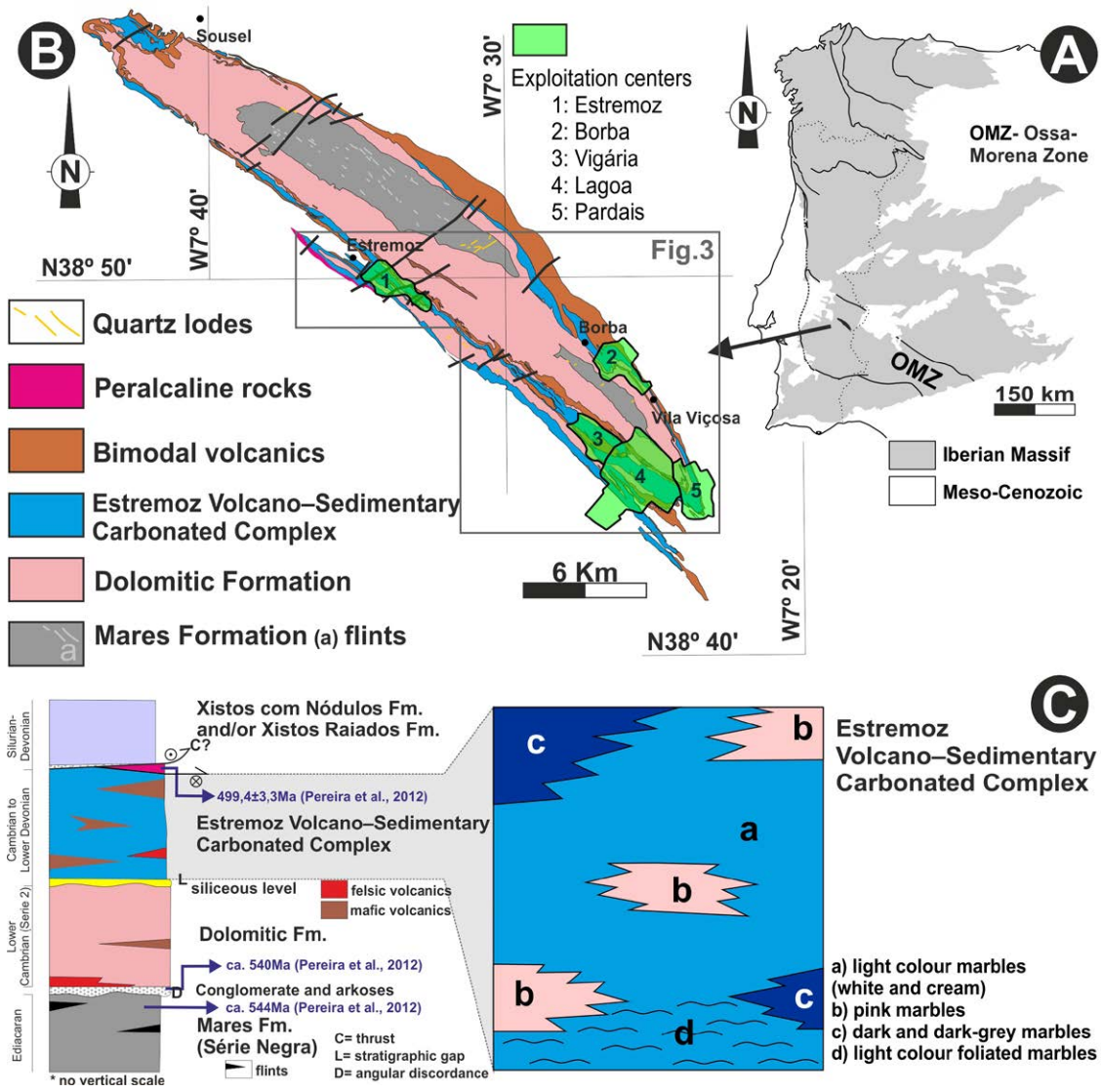

Figure 1. Geological and geographical framework of Estremoz Marbles (A): (B) Geological map of Estremoz Anticline (simplified from Moreira y Vintém, 1997) and (C) general stratigraphic column (adapted from Menningen *et al*., 2018).

Figura 1. Marco geológico y geográfico de los mármoles de Estremoz (A): (B) Mapa geológico del Anticlinal de Estremoz (simplificado de Moreira y Vintém, 1997) y (C) columna estratigráfica general (adaptada de Menningen *et al*., 2018).

However, the archaeological evidence of ancient quarrying in Estremoz Anticline is relatively scarce. As the marble from this region still stands for a major economic asset, has been exploited extensively during contemporaneous times (Fig. 2), most of the Roman exploitation remains was seriously erased. Only in specific situations they have survived, although due to a lack of intensive field survey, their identification is hazardous and not systematic.

Figure 2. Southeast termination of Estremoz Anticline (southwest flank) landscape view, showing the current exploitation area of Vigária – Lagoa region, where there have been several ancient marble exploitations. This area corresponds to a second-order syncline where marbles exploited as ornamental rocks reach depths close to 400 metres.

Figura 2. Vista del paisaje del extremo sureste del Anticlinal de Estremoz (flanco suroeste), que muestra la zona de explotación actual de la región de Vigária – Lagoa, donde se han realizado varias explotaciones de mármol antiguas. Esta zona corresponde a un sinclinal de segundo orden donde los mármoles explotados como rocas ornamentales alcanzan profundidades cercanas a los 400 metros.

In the present paper, it is summarized the available evidence remains, most of them unpublished, and a systematic study of historical quarries, which had never been undertaken for this region (see Justino Maciel, 1998 and Carneiro, 2022 to summary the description of the previous reported archaeological sites, also included in this paper). This paper synthesises and discusses the archaeological evidence unearthed over several decades, aiming to provide the first comprehensive analysis of the historical extractive activities in the Estremoz Anticline. While the exploitation of marble in this region can be attested, though mostly indirectly, for the better part of the past two millennia, this paper will delve predominantly into the extractive activity that occurred during the Roman period, as most of the evidence unearthed seems to be related with this chronology.

2. GEOLOGICAL FRAMEWORK OF THE ESTREMOZ MARBLES

The Alentejo region contains several occurrences of Palaeozoic calcitic marbles, mostly on the tectonostratigraphic zone known as the Ossa-Morena Zone (Fig. 1A), in the Southern branch of the European Variscides (e.g., Dias *et al.*, 2016). Indeed, from the Alter do Chão - Elvas to Vila Verde de Ficalho region, there are several marble occurrences with similar stratigraphic successions but showing different degrees of metamorphism (e.g., Oliveira *et al.*, 1991; Gomes & Fonseca, 2006; Lopes & Martins, 2015; Moreira *et al.*, 2019, 2020; Lopes *et al.*, 2024; Roseiro *et al.*, 2025), some of those showing evidence of exploitation since the Roman period. Among all these occurrences, it stands out the Estremoz Anticline (Fig. 1B), a 1st order structure in Iberia Variscides that extends up from Sousel, in the NW termination, to Alandroal, in the SE (e.g., Lopes, 2003; Lopes & Martins, 2015; Pereira *et al.*, 2012; Moreira *et al.*, 2014), where the Estremoz Marbles are exploited in a geological unit known as Estremoz Volcano-Sedimentary Carbonated Complex (Fig. 1C). First formally described by Silva &

Camarinhas (1957), the stratigraphic sequence includes (Fig. 1C) (Gonçalves, 1970, 1972; Gonçalves & Coelho, 1974; Gonçalves & Oliveira, 1986; Oliveira *et al.*, 1991; Lopes, 2003, 2007; Pereira *et al.*, 2012): (1) an Ediacaran unit composed of metagreywackes, black schists and metacherts (Mares Formation, Série Negra succession), cropping out in two elongated NW–SE trending ribbons in the core of the Estremoz Anticline; (2) a Cambrian arkosic meta-sandstones, which unconformably overlie the Série Negra succession, followed by the Dolomite Formation, composed of dolomite marbles of approximately 400 m thick; (3) over the Dolomite Formation, a 50 cm to 5 m-thick silica-rich horizon is developed, showing pyrite at depth, which is transformed into iron oxide pseudomorph crystals at the surface; and finally (4) a calcite-rich marble unit with interbedded volcanic ashes, basalts, rhyolites and shales (originally 70–100 m thick). The geochemistry of the interbedded basalts and rhyolites indicates a within-plate environment, probably related to lower Palaeozoic rifting processes (Mata & Munhá, 1985). This calcite-rich marble succession is known as Estremoz Volcanic–Sedimentary Carbonated Complex, and its age is highly discussed (see Moreira *et al.*, 2019 for a discussion), being generally attributed to Cambrian to Lower Devonian. The Estremoz Anticline is surrounded by shales, black shales and black cherts from the Silurian to Devonian ages (Piçarra, 2000; Lopes, 2003, 2007; Moreira, 2017; Moreira *et al.*, 2019).

Resulting from regional tectonic processes related to Variscan Orogeny, namely shearing and thickening of the marble layers by folding, the marble succession thickness can reach over 400m (Lopes & Martins, 2015). Indeed, the stratigraphic sequence of the Estremoz Anticline was deformed and metamorphosed under greenschist to lower-amphibolite metamorphic conditions during the Variscan Orogeny (Devonian to Carboniferous; Lopes, 2003; Pereira *et al.*, 2012; Moreira *et al.*, 2019; Laranjeira *et al.*, 2023). The Variscan deformation and metamorphism in the Ossa-Morena Zone were responsible for the development of N110°–170°trending folds and ductile to brittle–ductile shear zones (Lopes, 2003; Pereira *et al.*, 2012). The general structure of the Estremoz Anticline resulted from the interference between two Variscan folding phases of wrenching. D_1 folds are associated with the development of shear zones and boudinage, showing the development of mylonitic foliation and stretching lineation parallel to the maximum elongation direction (170°–180°) and shear criteria (asymmetrical tails of porphyroblasts, C–S planes) consistent with top-to-the-north shearing. However, the general cartographic pattern of the Estremoz Anticline has mostly resulted from the D_2 folding episode, characterised by 110–130° striking, tight to close D_2 folds with vergence to the NE. The D_2 folds are associated with greenschist facies slaty cleavage and discrete brittle/ductile sinistral shear zones along the reverse limbs and stretched limbs of tight folds. These shear zones strike 110– 130° and have a gentle (10°) NW- or SE-plunging mineral lineation, parallel to the D_2 fold axis. The Late Variscan brittle deformation is also presented in two sets of arrays. The first is closely related with the D_2 folds and consists of subvertical NNE–SSW and ENE–WSW trending conjugate faults, frequently associated with NE– SW, subvertical tension cracks. The second fault set is characterised by sub-vertical NNW–SSE and NE–SW trending faults. Acting together and having associated exploitation tension release fracturing, all these fractures cause a high density of discontinuities that results in a lower rate of the marble exploitation (in some cases 3.5%). Frequently, ENE–WSW to NE-SW left lateral faults are filled with Mesozoic dolerites (locally named as “Cabo real”). Indeed, the NNW–SSE shear zones, associated with the stretched limbs of the D_2 folds together with the dolerite filled ENE–WSW to NE-SW discontinuities, define sub-rectangular boundary array domains that, frequently, delimit the quarries. Finally, discrete and less frequent left-lateral NNE–SSW faults and conjugate right-lateral NNW–SSE faults, both vertical, which intersect all the previous described structures, are found, being related to the expression of the Alpine Orogeny in the region and cause more fracturing of the marble.

The Estremoz Marbles exhibit characteristic colours, patterns, hues and textures well known in the industry, presenting dozens of commercial names which reflect this variety. Despite the wide variety of colours and textures, three main marble typologies are well known: (1) the light colour (white to cream) marbles, commonly with red to orange, brown or dark-grey stripes (Pele de Tigre [Tiger skin] marbles); (2) the pink marbles, with different tonal intensities and sometimes exhibiting thick green mica-rich layers; and (3) the dark-grey marbles, also with different tonal intensities, generally known as Ruivina Marble. All these typologies are exploited in the present times, also pointing to their use during Roman times (Moreira, 2022).

2.1. Mineralogical and geochemical features: key to trace geological sources of Estremoz Marbles

The Estremoz Marbles are pure marbles (carbonate phases are generally higher than 90%), with exceptionally low content in silicate, oxides and sulphide phases. The main carbonate phase is calcite, and dolomite is generally rare or absent (commonly less than 10%, although sometimes reaching 15% namely in marbles from the bottom of the sequence or resulting of secondary dolomitisation processes) (Casal Moura *et al*., 2007; Menningen *et al*., 2018; Moreira *et al*., 2019). The accessory phases are mainly composed of quartz and muscovite, and less frequently feldspar, plagioclase, biotite, pyrite, iron oxide mineral phases, zircon, chlorite, rutile, apatite, tourmaline and titanite (Lapuente & Turi, 1995; Casal Moura *et al*., 2007; Lopes & Martins, 2015; Menningen *et al*., 2018; Moreira *et al*., 2019, 2020). The dark-grey marbles also show disperse carbonaceous matter (Casal Moura *et al*., 2007; Moreira *et al*., 2019). Pink marbles with green bands are the most impure marbles, being mainly composed of green mica, quartz, chlorite and feldspar; the actinolite-tremolite is absent (Lopes & Martins, 2015; Moreira *et al*., 2020). The Estremoz Marbles are fine to medium grained (average grain size between 0.5 to 1.0 mm, although can range between 0.2 to 4.0 mm) (Lapuente & Turi, 1995; Lapuente & Blanc, 2002; Menningen *et al*., 2018) and generally have granoblastic (homeo- to heteroblastic) texture, although granolepidoblastic and mylonite textures can also be recognised (Lapuente & Turi, 1995; Lapuente & Blanc, 2002; Lopes & Martins, 2015; Menningen *et al*., 2018).

Some whole rock geochemistry studies, using different geochemical methods, have been performed in Estremoz Marbles (e.g., Casal Moura *et al*., 2007; Gomes Silva, 1989; Lapuente, 1995; Martins, 1996; Menningen *et al*., 2018; Ontiveros *et al*., 2020), mainly to characterise these dimension stones; these studies focus on the characterisation of major elements from Estremoz Marbles, and only a few studies include trace elements, including REE (Lapuente, 1995; Casal Moura *et al*., 2007; Ontiveros *et al*., 2020). The content of major elements does not allow a clear differentiation between the different marble typologies (Moreira, 2022), nevertheless, the whole rock geochemistry can be used as proxy to identify the provenance of marbles used in historical and archaeological contexts (Lapuente, 1995; Ontiveros *et al*., 2020, 2024), namely when is supported by careful petrographic studies (textural and mineralogical), also including cathodoluminescence and X-ray diffractometry techniques.

The isotope geochemistry has been used as a proxy to trace the provenance and source of marbles in archaeological/historical contexts (e.g., Lapuente *et al*., 2000; Morbidelli *et al*., 2007; Origlia *et al*., 2011; Antonelli *et al*., 2009, 2015; Moreira *et al*., 2020). First approaches to the isotopic characterisation of Ossa-Morena Zone marbles, namely to the Estremoz Anticline ones, were carried out using stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) (e.g., Cabral *et al*., 1992, 2001; Perez *et al*., 1998; Lapuente *et al*., 2000; Lopes *et al*., 2000) and, more recently, the $^{87}Sr/^{86}Sr$ isotope ratio was also applied to discriminate the Ossa Morena Zone marbles and to trace the provenance of archaeological pieces (e.g., Morbidelli *et al*., 2007; Taelman *et al*., 2013; Moreira *et al*., 2020). Both techniques allow, in many cases, a clear differentiation between the Ossa Morena Zone and the Mediterranean marbles (e.g., Italic or Anatolian Peninsulas, Greece or Betic Mountain belt) (Zöldföldi, 2011; Moreira *et al*., 2020; Wielgosz-Rondolino *et al*., 2020). However, both methods do not finely distinguish the Ossa Morena Zone marbles from each other and must be accompanied by careful complementary petrographic studies (Moreira *et al*., 2020). Summary of isotope values of the Estremoz Marbles and other OMZ marbles are synthesised in Moreira *et al*. (2020).

3. HISTORICAL CONTEXT

The use of stone materials for construction can be traced to pre-Roman periods in the territory that would become the province of *Lusitania*. However, the integration of this region into the Roman world led to substantial changes in several aspects of stone exploitation, trade and use, significantly increasing volumes, the range of different applications and, particularly, the variability of lithotypes exploited. Indeed, during the government of Augustus (r. 27 BC – 14 AD), new architectural concepts emerged in this territory, namely in the newly established urban centres with public and increasingly monumental buildings. This resulted in an exponential increase in the use of stone resources and the

widespread development and use of decorative stone elements, frequently produced out of crystalline rocks such as marble. The relevance of the latter is attested not only in Rome itself, where, according to Suetonius (Aug., 28, 3), Augustus himself arguably said he found a city of bricks and left a city of marble, but also at a local scale, particularly in the provincial capital, *Augusta Emerita*, founded *ex novo* around 25 BC, where the older phases of the forum and the oldest temple were built with local granite that was subsequently plastered to give the appearance of marble (Fusco & Mañas, 2006).

From this period onwards there was an increasing demand and, therefore, an exponential expansion of trade and use of different types of ornamental stones which, as a luxurious element displaying a subjacent allure of wealth and economic status (Fant, 1988), were widely used for architectural embellishment (Taelman *et al*., 2013; Taelman, 2014), being conspicuously used in lavish public decorative programs. Though the imperial agency is frequently assumed to be the main factor when discussing demand, exploitation and stone trade, it seems relevant to argue that local agents might have played a crucial role in the extractive industry. Indeed, following the example and new models emanating from Rome, and basing local power on the concept of *imitatio Augusti*, provincial elites could have been the main promoters of the development of trade in marble resources at a local and regional scale, motivating the exploitation of a growing number of local quarries, mostly starting right at the beginning of the 1st century AD (Fusco & Mañas, 2006). This local agency is attested by inscriptions found across *Lusitania* (e.g. CIL II 183 and CIL II 2479), produced to note the sponsored construction or renovation of public buildings in various urban centres by distinct local, Romanised elite members.

The decline of this private evergetism and the associated relevancy of urban public architectural munificence throughout the 3rd century (Marano, 2016) resulted in substantial changes in the stone trade, affecting demand and consumption patterns. In particular, during the Late Roman period, there was a significant reduction of primary exploitation, attested by a generalised abandonment of quarry areas across the whole Roman world (e.g., Gutiérrez García-M., 2011), resulting in a supply increasingly characterised by the spoliation and reuse of stone materials extracted from previous building programs (Alchermes, 1994), having, therefore, a significant impact on the urban landscapes of this period. These aspects and the socio-political changes and religious dynamics observed throughout Late Antiquity increased the economic and symbolic value of decorative stones, particularly marble, which became an indicator of wealth, social status, and Roman identity.

The province of *Lusitania* was endowed with good-quality marble sources, namely in the Estremoz Anticline, where Roman exploitation can be traced to the 1st century AD (Carneiro, 2019). Notwithstanding, direct evidence of this activity is still relatively scarce and relevant aspects, such as the ownership and organisation of the extractive process and the inherent coordination, remain largely unknown. Whereas in the neighbouring region of *Baetica* there are literary and epigraphic references (CIL II 1043) attesting to the existence of a *pagus marmorarius*, possibly located in the area of Almaden de la Plata (Taylor, 2020), and a professional group, the *serrarii* (CIL II 1131, 1132), specialised in stone sawing (Padilla-Monge, 2018), in the area of *Lusitania* the evidence is comparatively scarcer. Relying exclusively on the epigraphic evidence, there are but a few inscriptions, two referring to individuals identified as *marmorarius* (IRCP 269, 497) and another who was possibly a *subselliarius* – a manufacturer of marble seats (Encarnação, 1987).

Although most of the academic interest has been centred on the Roman period, the marble of the Estremoz Anticline was exploited and used in subsequent periods, particularly from the late medieval period onwards (Lopes & Martins, 2015, 2018; Mourinha & Moreira, 2019). This stone material was mostly used locally in several medieval building programs in the town of Estremoz and was also extensively used in the early modern ducal palace of Vila Viçosa (Durão, 2017). Nevertheless, as for the Roman period, the extent and organisational aspects of marble quarrying in these later periods remain largely unexplored. As mentioned earlier, archaeological sites with evidence for stone exploitation and processing are limited, as most findings were discovered with the advancement of industrial exploitation underway in recent decades, and the region still lacks extensive, systematic surveying that could significantly expand the existing evidence and, subsequently, the current knowledge.

4. METHODOLOGY

4.1. Remote Sensing Methodologies

High-resolution aerial images are crucial in archaeological studies and preservation assessments as they reveal the distribution of vestiges and the spatial relationships within the location, outlining the full extent of historic remnants. In this study, a DJI Mavic 2 Pro was used to survey the location, flying at an altitude of 30 metres and capturing 252 photos with 60-80% side and front overlap along a planned flight path. Additionally, 10 ground control points (GCPs) were measured across the area of interest using a Leica GS15 differential GPS to ensure the accuracy and precision of the generated orthophotomap. The captured images and GCPs were processed using Agisoft Metashape Professional software, generating a detailed Orthophotomap and a Digital Elevation Model.

4.2. 3D model reconstruction

3D models created using Light Detection and Ranging (LiDAR) technology facilitate non-destructive archaeometry studies on archaeological vestiges, enabling the measurement of carving distances, tool width, tool length, and indentation angles, and markings specific to that period. In this work, a Creality CR-Scan Ferret Pro was used on target outcrops featuring archaeological evidence. The portable device uses LiDAR to create 3D with an accuracy of up to 0.1 mm and a resolution of 0.16 mm. To complement the LiDAR models, a photogrammetric reconstruction of the outcrops was performed using a DJI Mini 2 drone and capturing photos from multiple viewing angles at varying heights.

5. ESTREMOZ ANTICLINE MARBLES: EXPLOITATION DURING ROMAN PERIOD

The Estremoz Marble (a general term to define all the marbles exploited in the marble triangle of Borba-Estremoz-Vila Viçosa) still does not occupy its rightful place in research into the most important stone resources in Roman times. For example, the irreplaceable reference manual on construction in Roman times, written by Adam (1989), does not mention the marbles of the Estremoz Anticline. But this circumstance also stems from another reality: there has never been any serious, sustained and committed research to characterise and publicise the areas of marble production in Roman times on this region as it happened in many locations (Italy, Turkey, Greece, Egypt, Spain, etc.); no systematic fieldwork was carried out to document the Roman quarries in this region when the boom in exploitation began in the beginning of the 1980s resulting in many traces being erased without any archaeological monitoring. The same occurs until present days, with no relevant archaeological and geological exploration projects or programs in this region, despite the significance of these marbles in the construction of some Roman towns or villae (e.g., Cabral *et al.*, 2001, 2004; Justino Maciel *et al.*, 2006; Antonelli *et al.*, 2009; Taelman *et al.*, 2013; Lapuente *et al.*, 2014; Moreira *et al.*, 2020) or even the discovery of several archaeological sites, most of them preserved by industrial companies.

Indeed, in addition to the finds preserved by the company Solubema during 70's and 80's, a single example has been saved, documented by the remains of Roman exploitation in the Lagoa quarry (Vila Viçosa), here described for the first time, and a few isolated founds that subsequent research has made it possible to document (Fig. 3).

This situation also stems from another fact upstream of current research: the origin of the marbles and stone production areas are frequently omitted in the local sources, with no ancient literary references whatsoever.

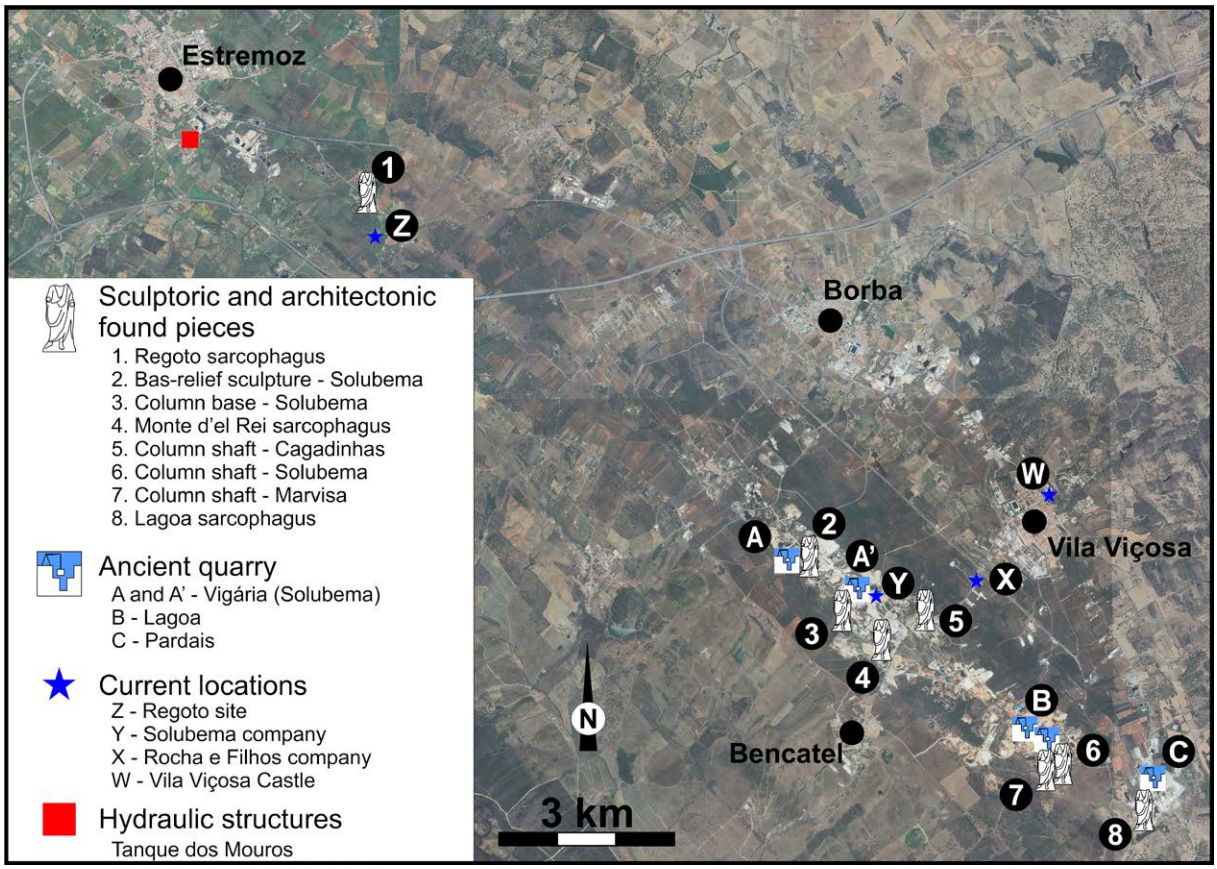

Figure 3. Location of archaeological sites studied in this paper (symbols represent the geographic position).

Figura 3. Ubicación de los yacimientos arqueológicos estudiados en este trabajo (los símbolos representan la posición geográfica).

5.1. The Techniques

The dismantling method used to exploit the marble was considered based on the geological and geomechanical features of the massif, as well as the chromatic appearance, crystallinity and homogeneity of the pattern, since a rock was extracted, fundamentally for ornamental purposes.

At that time, the specificity of the work carried out in an extractive unit forced the creation of different categories of workers, with "marmists" who were excavators, and "squarers" dedicated to squaring the blocks, giving them a regular, predominantly parallelepiped shape, using a hammer and chisel and the *"serraris"* sectors that cut the blocks into sheets with the help of hand saws (Conti & Bessi, 1996; Fig. 14A).

The main cutting technique for separating rock masses from the massif was known as "Roman Cut", having been used until the introduction of explosives in the 19th century. The tools used were essentially wedges, chisels, hammers, sledgehammers, shovels, pickaxes, levers and hoes. Wedges and feathers were used to open natural fractures, while sledgehammers and chisels were used to make cuts or grooves that led to the division of the dismantled masses into commercial.

Thus, the "Roman Cut" was preceded by a detailed analysis of natural marble anisotropies (bedding, foliation, cleavage, banding and fractures), which would constitute favourable cutting planes or pre-defined directions, in which incisions were made, where wooden wedges soaked in water were introduced. When atmospheric conditions provided this, the freezing of the water increased the volume, increasing fracturing and the consequent individualisation of the block.

The cuts according to the steepest line of the marble layer, called *"caesurae"*, were made with camarteles to the necessary depth, to individualise the blocks through V-shaped cuts, for later introduction of the wedges (Fig. 14B).

The use of wooden bars in the cuts made was also a common practice, especially in limestone massifs, where the bedding materialised in parallel discontinuities, facilitating the detachment of blocks. In marbles, it is the tectonic orientation (banding or/and the cleavage) that defines the directions of greatest weakness along which cutting or opening planes are easier.

The use of saws (Fig. 2A) cannot be excluded, even in the quarries of Vila Viçosa, given the discovery made in 2012 in a quarry in Pardais sector (see below), where, alongside the traditional "Roman Cut", perfectly smooth cuts appear, as mentioned later in this work.

Del Soldato & Pintus (1985), referring particularly to underground exploration in Italy, describe that after opening the tunnel, the width of the blocks was defined through the execution of two lateral slots that allowed two men with an iron saw large tempered and toothless to make the lower and posterior blows. The cutting action was aided by the introduction of water and silica sand. The block was removed using wooden or iron wedges. In the studied area, the underground exploration techniques were not found.

In most cases, the masses were sized, considering their purpose, volume and shape, to facilitate their transport and simplify their final treatment, which generally occurs in the quarry area, as proven by the several architectonic, sepulchral and sculptural abandoned pieces found in the Glória, Vigária, Lagoa and Pardais sectors (see next sections). It also should be emphasised that the transport of heavy loads from Estremoz Anticline to the main consumption areas (e.g. *Emerita, Olisipo* or *Ebora*) would preferably be carried out by ox vehicles, being complemented by fluvial transport when it is possible, implying a minimum transport time range between 15 and 40 hours, depending on the distance to the extractive area, which also implies the increase of costs (Trapero Fernandez *et al*., 2023). So, the transport of heavy loads occurs preferentially only to raw materials that stand out from other materials of local origin, and the marble from Estremoz Anticline should be seen in this way.

After being detached, the blocks were removed with the aid of iron levers in a purely physical, mechanical process, where the bar supported at a point multiplies the intensity of the applied force. In ancient times, experts knew this, making it possible to remove large volumes of rock. The multiplication of forces was also guaranteed with the use of pulleys and windlasses, sometimes applied to cranes of different types and complexity, as mentioned by Alarcão (2004), alluding to the simple gorge (rechamum), gorge with drum, inside the which evolved into a worker operating the crane and the *carchesium*. Interestingly, the cranes are made up of two thick beams joined together in an inverted V, slightly inclined towards the front and supported at the back by cables anchored in the ground, a model similar to current Derrick cranes.

Before total removal, the land was prepared, and its removal was conducted with the help of pack animals that pulled the stone blocks placed on wooden beams and carts.

In the quarries of the Estremoz Anticline, until the widespread use of mechanisation in the sixties of the 20th century, working conditions would not be very different, they were essentially based on animal strength, of men and pack animals, there is even a record photograph that illustrates these cases (i.e. Solubema S.A. and "Amigos de Vila Viçosa" association private photographic archives). Reports from former workers state that it was common for quarries to have more than thirty, sometimes sixty, workers. Accidents at work were quite common and often had an unhappy ending.

5.2. The Archaeological evidence

5.2.1. The Lagoa sector

5.2.1.1. The Marmoz quarry: *in situ* evidence of exploitation

The Marmoz quarry (Fig. 5) is undoubtedly a privileged place in the Estremoz Anticline, where traces of marble extraction in Roman times can still be found *in situ*. The marbles from this quarry are light coloured and tiger skin marbles (white with grey stripes), which outcrops in the upper levels of the quarry, where the ancient quarry extraction marks were found.

Although the quarry was also exploited in several periods during the 20th century, which is proven by the diversity of extraction marks and techniques found in quarry faces, it was preserved several alignments of holes for inserting wedges (one of those preserves a metallic feather discovered during the last excavation process; Fig. 4B), and several exploration front step marks. Also here, a negative mark of what may have been a column of around 5 metres long (it is not excluded that could be a block for carving a sarcophagus) is still preserved: the outcrop is cut into a sub-rectangular shape, presumably to extract the top that would have been worked elsewhere (figs. 6 and 7).

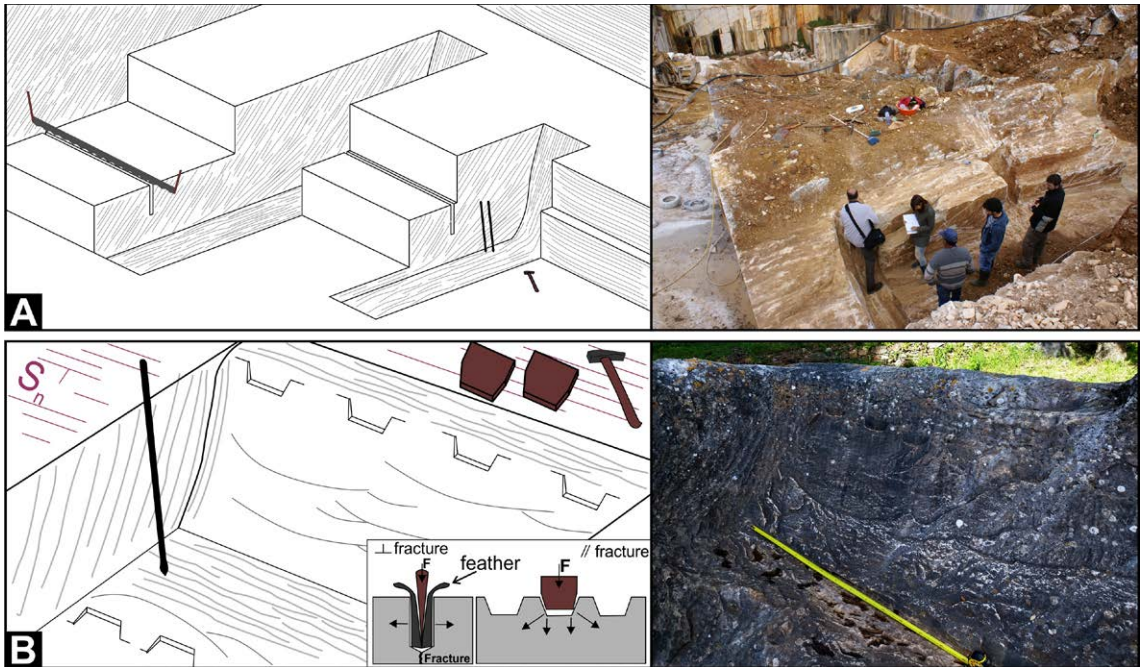

Figure 4. Diagrams illustrating the methods of dismantling the massif described in the text.
Figura 4. Diagramas que ilustran los métodos de desmantelamiento del macizo descritos en el texto.

Figure 5. Marmoz Quarry, the most extensive and better-preserved place of roman exploitation area. The bluish shaded areas mark the locations with a dense number of exploitation marks. The area on the left was found during the fieldwork for this article.

Figura 5. Cantera de Marmoz, el yacimiento romano de explotación más extenso y mejor conservado. Las zonas sombreadas en azul indican las ubicaciones con una alta concentración de marcas de explotación. La zona de la izquierda se descubrió durante el trabajo de campo realizado para este artículo.

Figure 6. General view of the Marmoz quarry, highlighting: (A) the site of a probable column extraction; (B) the places where wooden wedges were inserted to cut the marble using a sledgehammer and chisel; and (C) the well-defined marks for placing the wooden wedges.

Figura 6. Vista general de la cantera de Marmoz, destacando: (A) el sitio de una probable extracción de columna; (B) los lugares donde se insertaron cuñas de madera para cortar el mármol con un mazo y un cincel; y (C) las marcas bien definidas para colocar las cuñas de madera.

Figure 7. Details of the Marmoz historical quarry. (A) In the image's centre, the scar from removing a 5-metre marble column is evident; (B) as a rule, these marks for the insertion of wooden wedges are 20 cm wide at their widest and 10 cm at their narrowest, and their depth is around eight centimetres. Note that the cutting plane aligns with the regional metamorphic foliation of the second deformation phase; (C) this cutting direction does not correspond to any direction of structural weakness in the massif. At the same time, it is perpendicular to the metamorphic banding (S_0/S_1) and the regional metamorphic foliation (S_2), and is therefore more difficult to cut, having probably been done with a chisel and sledgehammer, leaving the grooves well preserved as can be seen in the pictures.

Figura 7. Detalles de la cantera histórica de Marmoz. (A) En el centro de la imagen, se aprecia la cicatriz de la extracción de una columna de mármol de 5 metros; (B) por lo general, estas marcas para la inserción de cuñas de madera tienen 20 cm de ancho en su punto más ancho y 10 cm en su punto más estrecho, y su profundidad es de unos ocho centímetros. Nótese que el plano de corte se alinea con la foliación metamórfica regional de la segunda fase de deformación; (C) esta dirección de corte no corresponde a ninguna dirección de debilidad estructural en el macizo. Al mismo tiempo, es perpendicular a las bandas metamórficas (S_0/S_1) y a la foliación metamórfica regional (S_2), y por lo tanto es más difícil de cortar, habiéndose realizado probablemente con cincel y mazo, dejando los surcos bien conservados como se puede ver en las imágenes.

As mentioned, there are many wedge alignments, some of them around the column negative (figs. 6 and 7), showing the process of selecting the raw material and the extraction strategy, which favoured the tops where the natural karst geoforms and fractures allowed less investment in human action. But not only in this archaeological quarry area are the wedge mark alignments found, and in two other locations in the same quarry, where these marks are also found. In one of these areas, exploitation front steps are found, showing wedge marks and cutting groove marks resulting from the use of sledgehammers and chisels. The use of wedges was made carefully, using the main anisotropies found in these marbles to benefit the marble exploitation (Fig. 8). Indeed, the progression of ancient exploitation is made availing the banding plane (S_0/S_1) and S_2 foliation, this is, the emplacement of the wedges was carefully chosen to take advantage of existing almost orthogonal structural anisotropies, thus allowing to remove blocks with a well-defined volume and shape.

Figure 8. Artificial steps obtained during the marble exploitation. (A) The three red arrows point to the trapezoidal-shaped holes for inserting wooden wedges dug into the plane of the metamorphic foliation. The white arrow points to a cut in a plane that is also parallel to the metamorphic foliation. This cut is the result of multiple subparallel perforations using a pneumatic air hammer, which was quite common before the diamond wire saw was introduced in the 1980s. (B) The combination of these two planes defines a stepped section that is clearly visible throughout the quarry. (C) The banding plane (S_0/S_1) defines gentle dipping planes to the north, while the regional metamorphic foliation (S_2) dips strongly to the south.

Figura 8. Escalones artificiales obtenidos durante la explotación del mármol. (A) Las tres flechas rojas señalan los orificios trapezoidales para insertar cuñas de madera excavadas en el plano de la foliación metamórfica. La flecha blanca señala un corte en un plano que también es paralelo a la foliación metamórfica. Este corte es el resultado de múltiples perforaciones subparalelas realizadas con un martillo neumático, que era bastante común antes de la introducción de la sierra de hilo diamantado en la década de 1980. (B) La combinación de estos dos planos define una sección escalonada que es claramente visible en toda la cantera. (C) El plano de bandas (S_0/S_1) define planos de suave inclinación hacia el norte, mientras que la foliación metamórfica regional (S_2) se inclina fuertemente hacia el sur.

In addition to the ancient quarry evidence described above, during the most recent prospecting campaign in the Marmoz quarry surrounding area, another superficial cavity was found (around 180 m to the west of the Marmoz quarry; see Fig. 5) with marks which proved the ancient exploitation of this area. Wedge marks and cutting groove marks were also found in this second quarry.

Both ancient quarries agree with the marble exploitation model previously proposed by Moreira & Lopes (2019) for the Estremoz Anticline during Roman times. The authors argue that all the exploitations are superficial (probably not exceeding a dozen of metres in depth) but probably are extensive in area.

The identification of exploitation sites requires the recognition of anisotropies and weaknesses of the marble massif, thus allowing the easier extraction of the marble resource. Indeed, all evidence of Roman exploration in the Estremoz Anticline was found near the surface levels, where karstified structures appear, indicating that this is a criterion used during the prospecting and exploitation process. The Roman "prospectors" would also consider the quality of the raw material, in this case the marble, and the existence and geometry of natural anisotropies (fractures, banding and cleavage).

Until now, the Marmoz quarry area (including the other ancient quarry recently discovered) has been spared by the contemporaneous industrial exploitations that surround it in all directions and has every potential to become an archaeological and cultural geosite that should be preserved (see discussion section).

5.2.1.2. Other findings in the Lagoa sector

The Lagoa sector is one of the most promising areas for an archaeological prospecting project (as well as the Vigária sector, which will be described below), since not only was an *in situ* quarry found, but also some unfinished Roman archaeological pieces were found in that area.

At the Solubema company's facilities, located in the Vigária sector (Fig. 3), there are three rough column fragments recently collected in the Lagoa sector (Fig. 9), being displayed alongside the preserved remains discovered *in situ* in the Vigária area during contemporaneous exploitation. The columns were acquired and preserved by the company Solubema, S.A.

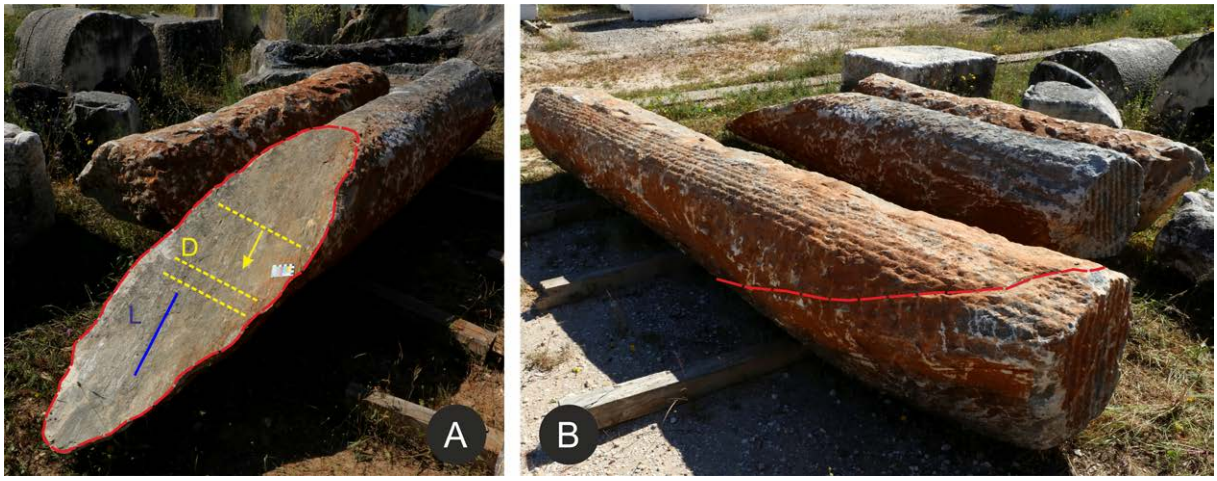

Figure 9. Three columns found in a historic quarry in the Lagoa area. The reason for abandoning this column is obvious and is related to the discontinuities relative to the open schistosity plane (underlined by the red dashed line in (A) and (B)), essentially made up of phyllosilicates. In this plane it is possible to identify the regional mineral stretching lineation (L), and the plane itself presents ladder grooves (D) that indicate the direction of shear associated with the genesis of these planes. In this case, it is a left shear component, as would be expected and is known regionally. It should be noted that in the case of macroscopic hinges, these planes of discontinuity may not coincide with the metamorphic band inherited from the sedimentary sequence, which may have misled explorers.

Figura 9. Tres columnas halladas en una cantera histórica en la zona de Lagoa. El motivo del abandono de esta columna es evidente y se relaciona con las discontinuidades respecto al plano de esquistosidad abierto (subrayado por la línea discontinua roja en (A) y (B)), compuesto esencialmente por filosilicatos. En este plano es posible identificar la lineación de estiramiento mineral regional (L), y el plano mismo presenta surcos en escalera (D) que indican la dirección de cizallamiento asociada a la génesis de estos planos. En este caso, se trata de un componente de cizallamiento izquierdo, como cabría esperar y es conocido regionalmente. Cabe señalar que, en el caso de charnelas macroscópicas, estos planos de discontinuidad pueden no coincidir con la banda metamórfica heredada de la secuencia sedimentaria, lo que pudo haber confundido a los exploradores.

The columns are made in tiger skin marble (in this case grey colours dominated), presenting 3 to 5 metres long, and displaying different surfaces with chisel and wedge marks (Fig. 9). They were probably abandoned on site because of natural cracks (Fig. 9). Their exact original location is approximate, and oral testimony tells they were discovered in the 80's at a shallow depth, embedded in soil. Their diameters and marble type are coherent with the similar marble columns of the Theatre of Merida in Spain (see section about use of Estremoz Marble in Roman sites). At Rocha & Filhos, Lda company (Vila Viçosa), in the factory next to the offices, the company has two other unfinished columns, in dark blue marble (commercial variety called Ruivina), and some other pieces found, in the 1980's, probably from its quarry in the Lagoa sector, although the precise location is unknown (Fig. 19D).

The existence of unfinished archaeological pieces set aside near the exploitation sites, also agrees with the model of Moreira & Lopes (2019), that argues that most of the sculptural pieces are carved on site, this is the extraction and initial processing of marble was carried out *in situ*, extracting the already semi-worked pieces from the rock mass. This would allow the volume and weight transported to be reduced, thus decreasing the cost of transport, as also argued by Trapero Fernandez *et al*. (2023). This implies a specific work organisation, with specialised workers labouring at the extraction site, which is also in accordance with the occupation models previously proposed for the region (e.g., Carneiro, 2014).

Although it cannot be the rule, because in some cases intact blocks could be extracted, the presence of a set of semi-finished sculptural and architectonic pieces close to extraction sites, not only here but also in Vigária, Pardais and Gloria sectors (see next sections), strengthens the proposed model.

5.2.2. The Pardais sector

In this sector, an ancient quarry site was discovered in 2012, during operations to widen an ABV, Lda. company quarry area. After cleaning, small centimetric benches with grooves typical of the "Roman cut" stood out, with N30°W orientation, corresponding to the main tectonic planar fabric (S_2, locally known as "corrume"; Fig. 10). This orientation corresponds to a preferential crystallographic alignment of calcite crystals that define well-defined planes of anisotropy and with behaviour like the schistosity found in pelitic rocks (metavolcanics and schists) and often interstratified with the purest carbonate facies (marble). This feature was known in antiquity because the cutting directions prevented this direction of structural weakness, obtaining better yields. This ancient quarry site is characterised by tiger skin and Ruivina marbles.

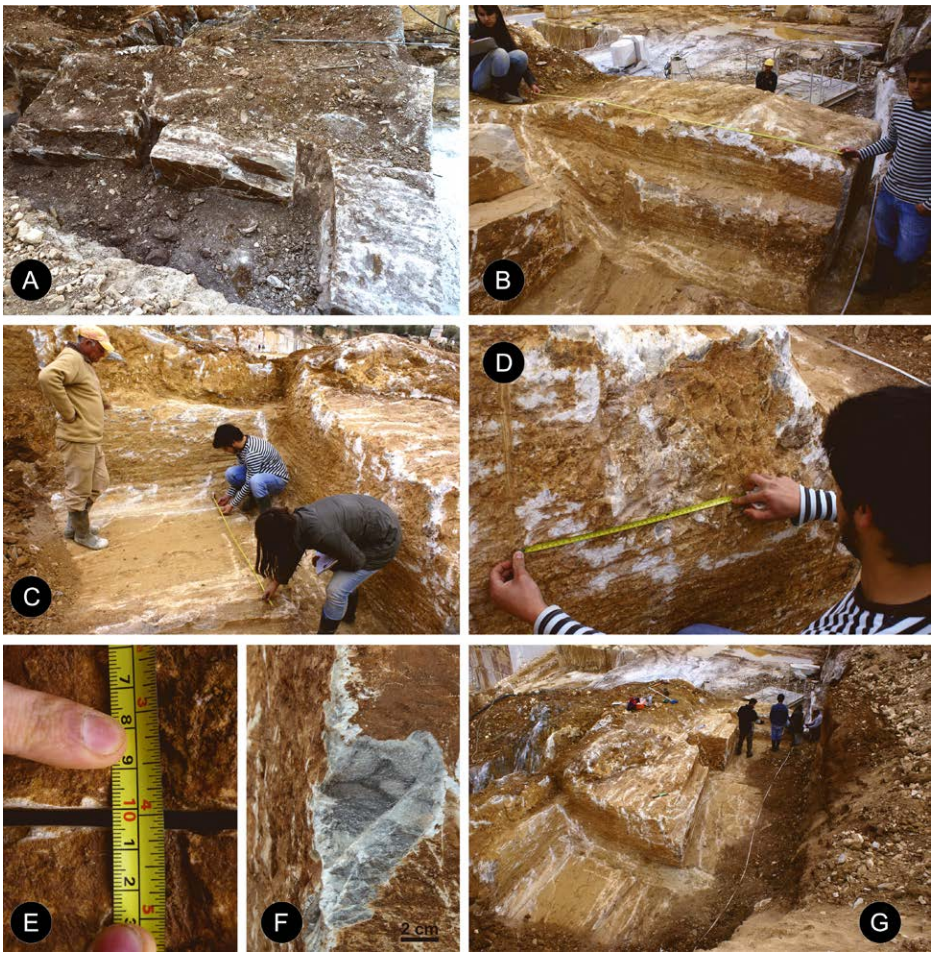

Figure 10. (A) to (G) various stages of cleaning work and data recording in the historic quarry of Fonte da Moura, Pardais, Vila Viçosa. In (F) the recent fracture shows that this is a bluish-grey, veined marble with a white background, commercially known as "Pele de Tigre" (Tiger Skin).

Figura 10. (A) a (G) diversas etapas de los trabajos de limpieza y registro de datos en la cantera histórica de Fonte da Moura, Pardais, Vila Viçosa. En (F), la fractura reciente muestra que se trata de un mármol veteado de color gris azulado con fondo blanco, conocido comercialmente como "Pele de Tigre" (Piel de Tigre).

The exploration method included the opening of small decimetre channels, individualising the benches, thus allowing cutting using a saw (figs. 4A and 11), recorded in the smooth strokes, evident in two of the benches. This procedure allowed the extraction of blocks or plates with better finishes (Fig. 10).

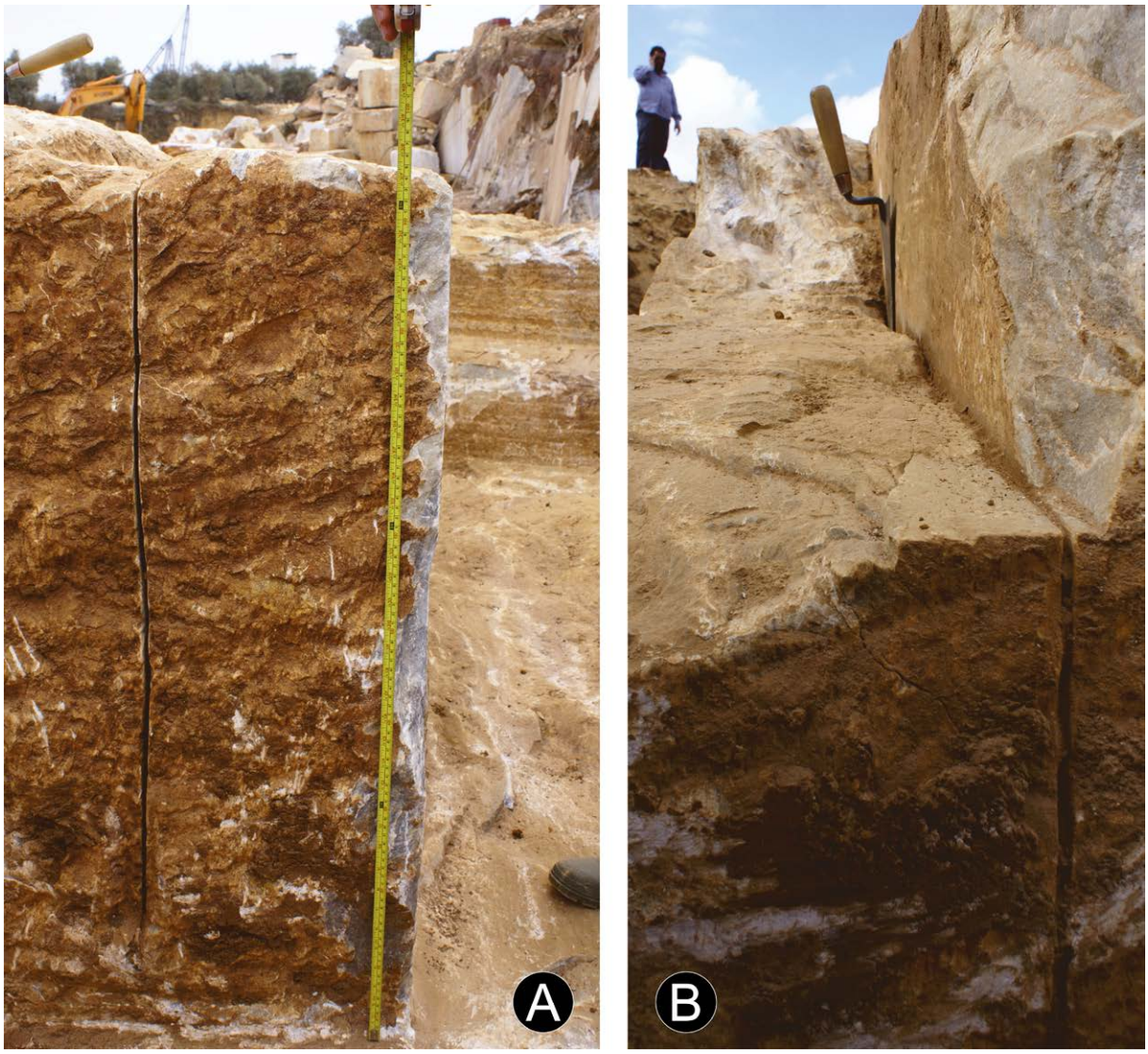

Figure 11. Perfect cuts made with a saw were found at this site (A). We can only add that in some strokes the dust residue from the cut was still present (B); however, all the earth covering the outcrop was sieved and no artefacts were found.

Figura 11. En este sitio se encontraron cortes perfectos realizados con sierra (A). Cabe añadir que en algunos trazos aún se observaban residuos de polvo del corte (B); sin embargo, se tamizó toda la tierra que cubría el afloramiento y no se hallaron artefactos.

After excavation, cleaning and measuring on site all the archaeological structures of the ancient quarry site (Fig. 10), it was agreed with the company for the total preservation of archaeological vestiges of the ancient quarry for later museumisation. Indeed, the company extracted all the ancient quarry remains in 3 distinct blocks, taking responsibility for preserving them in the company facilities until the museumisation process occurs.

In addition, one of the most important examples of ancient quarrying in this area occurs in the vicinity of the S. Marcos site (near Fonte da Moura quarry, Pardais), but, unfortunately, the contemporaneous work to expand the quarries in this area has not been archaeologically accompanied. As a result, it is impossible to confirm the ancient references, which mention abundant evidence of exploitation in Roman times. Of particular note are the passages in the work of Mário Saa (Saa, 1956: 138) who, not being an archaeologist but having a deep knowledge of the area, mentions discoveries of “marble columns (stone from the region), ashlars, floors of the usual polychrome mosaic (in profuse quantity), tiles, objects, inscriptions, everything appears there […]” [own translation], surely based on impressions taken in the

field. A double sarcophagus was also found *in situ* (Fig. 12) and is now on display at the Vila Viçosa Hunting and Archaeological Museum. According to Justino Maciel (1998), the dimension and geometry of the Pardais double sarcophagus, carved in marble outcrop, are congruent with those of others clearly from Roman times. According to the report performed by Bairrão Oleiro (1966), the ancient quarry site where the double sarcophagus is found is located at 2 metres deep relative to the topographic line. The double sarcophagus presents thin and planar walls, and guidance lines which should assist the cutting work to separate both sarcophagi (Bairrão Oleiro, 1966). According to the same report, at the head of one of the sarcophagi, the cutting process was initiated using a saw, as observed in the previously described Pardais ancient quarry. Finally, the report also emphasises that the archaeological site shows several wedge mark alignments, like those described in the Marmoz quarry site.

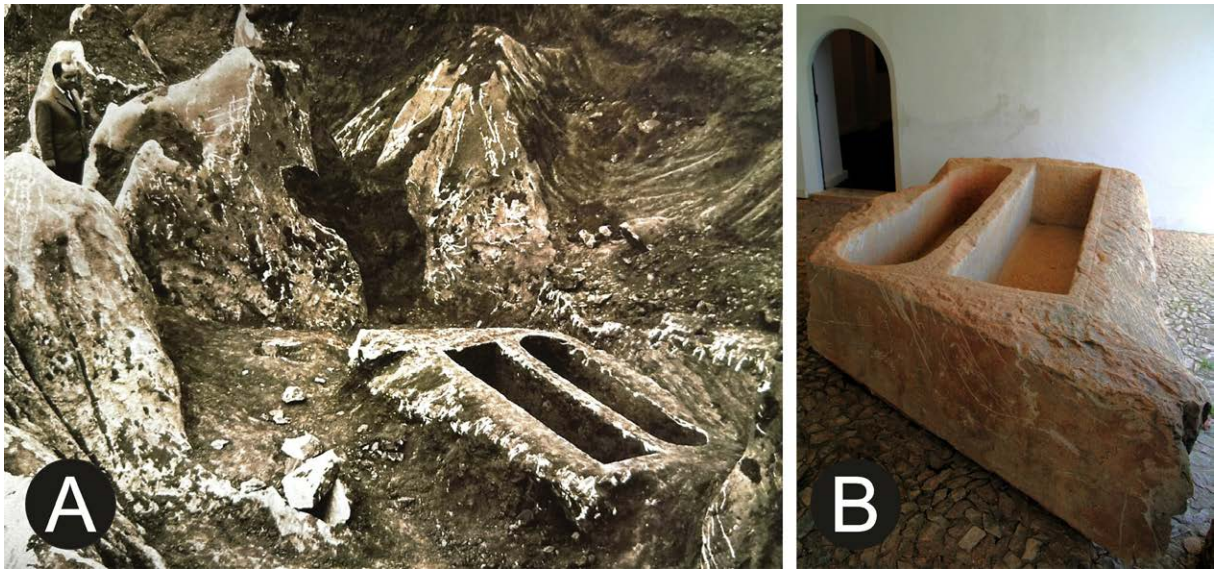

Figure 12. Double sarcophagus found in António Madas Rocha & Irmãos ancient contemporaneous quarry in São Marcos (Pardais, Vila Viçosa), probably in the sixties of the 20th century (Bairrão Oleiro, 1966). (A) a photograph of the find *in situ*, kindly provided by Vila Viçosa City Council and (B) the current situation on display at the Vila Viçosa Hunting and Archaeological Museum.

Figura 12. Sarcófago doble encontrado en la antigua cantera contemporánea de António Madas Rocha e Irmãos en São Marcos (Pardais, Vila Viçosa), probablemente en los años sesenta del siglo XX (Bairrão Oleiro, 1966). (A) una fotografía del hallazgo *in situ*, cedida amablemente por el Ayuntamiento de Vila Viçosa y (B) la situación actual expuesta en el Museo Arqueológico y de Caza de Vila Viçosa.

The continuation of exploitation activities until the present day changed the landscape to such an extent that the places described in historical documentation are completely unrecognisable today (Fig. 13).

5.2.3. The Vigária sector

The Solubema – Sociedade Luso Belga de Mármores, S.A. marble company started quarrying in 1928 in the Vigária area. Oral testimony of the antique evidence found at the start of the extraction seems to mention some surfaces locally showing cuts and negative hollow shape at a very superficial level that may therefore have been erased by the early start of contemporary works (Fig. 14). Even so, some of these marks can still be found *in situ* (Fig. 15).

The visible evidence documented is found in a secondary context, properly exhibited, stored and documented by the company exploring the deposit: blocks with wedges and unfinished marble cylinders, perhaps extracted for future columns, capitals and maybe sarcophagi, but also a short marble column extraction negative hollow trace conserved on a properly extracted block.

One of the most relevant testimonies of the Roman exploitation in the Estremoz Anticline is a bas-relief with a lying figure, possibly an aquatic deity, found *in situ* in the Vigária sector and probably from the 1st or 2nd century. This sculpture, as well as other architectural marble elements from the Vigária sector, were properly extracted and saved as a block, being also exhibited in the public garden of the castle of Vila Viçosa (Carneiro, 2014; 2019; figs. 16 and 17).

Figure 13. Current landscape at São Marcos (Pardais, Vila Viçosa).
Figura 13. Paisaje actual en São Marcos (Pardais, Vila Viçosa).

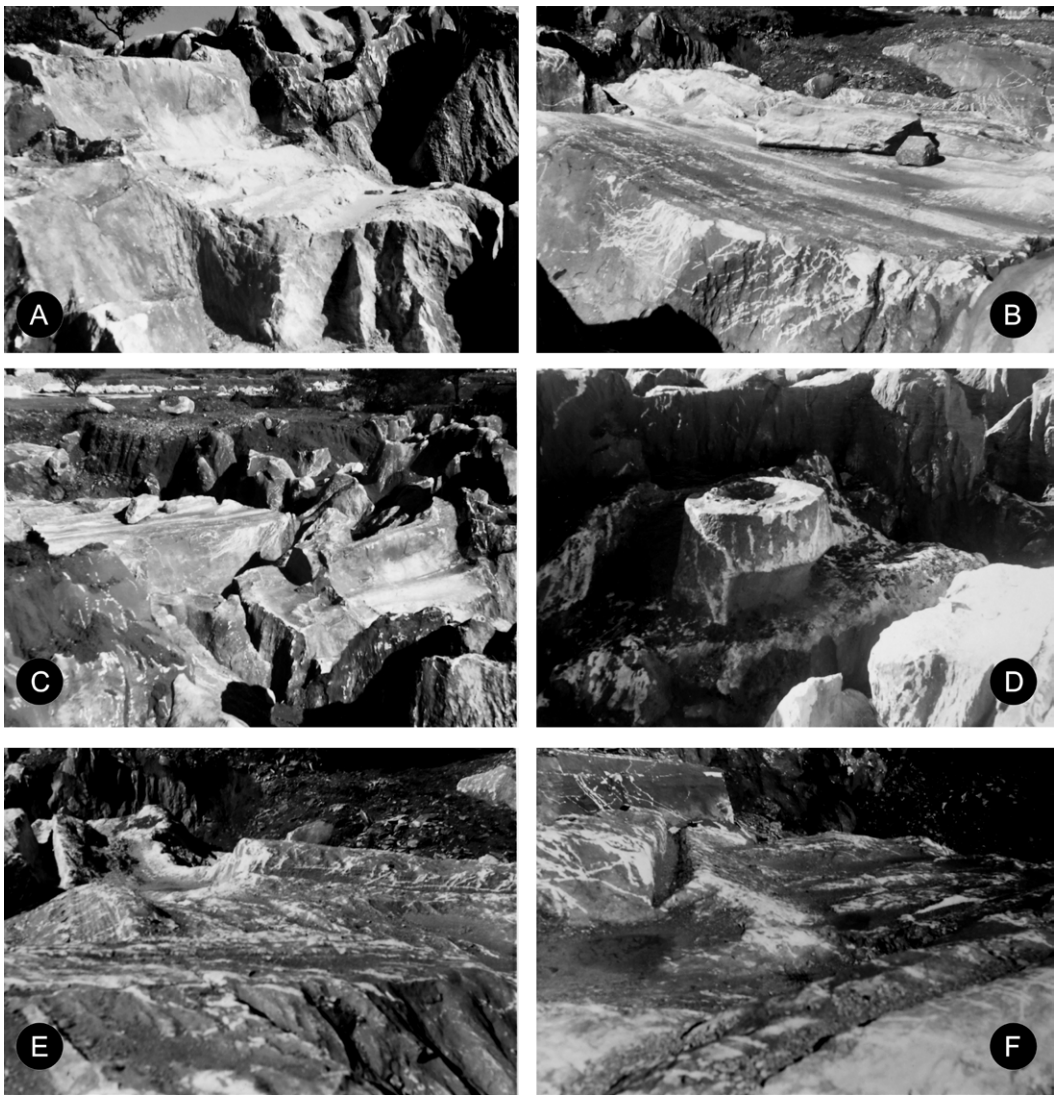

Figure 14. (A) to (F) quarries of the Solubema, S.A. company, illustrating several aspects of old mining workings uncovered during the stripping of the ground to open quarries in the 1950s and 1960s. Several unfinished pieces, most of them defective in some way, were found and stored on the company's premises.

Figura 14. (A) a (F) Canteras de la empresa Solubema, S.A., que ilustran diversos aspectos de las antiguas explotaciones mineras descubiertas durante la excavación del terreno para abrir las canteras en las décadas de 1950 y 1960. Varias piezas sin terminar, la mayoría de ellas defectuosas, fueron encontradas y almacenadas en las instalaciones de la empresa.

Figure 15. (A) and (B), in April 2024, as part of the research for this article, new marks were found in Solubema's VJ quarry (the "V" refers to the property "Herdade da Vigária" and the "J" to the name given sequentially to its quarries, which correspond to a single exploration area with 100 hectares).

Figura 15. (A) y (B), en abril de 2024, como parte de la investigación para este artículo, se encontraron nuevas marcas en la cantera VJ de Solubema (la "V" se refiere a la propiedad "Herdade da Vigária" y la "J" al nombre dado secuencialmente a sus canteras, que corresponden a una única área de exploración de 100 hectáreas).

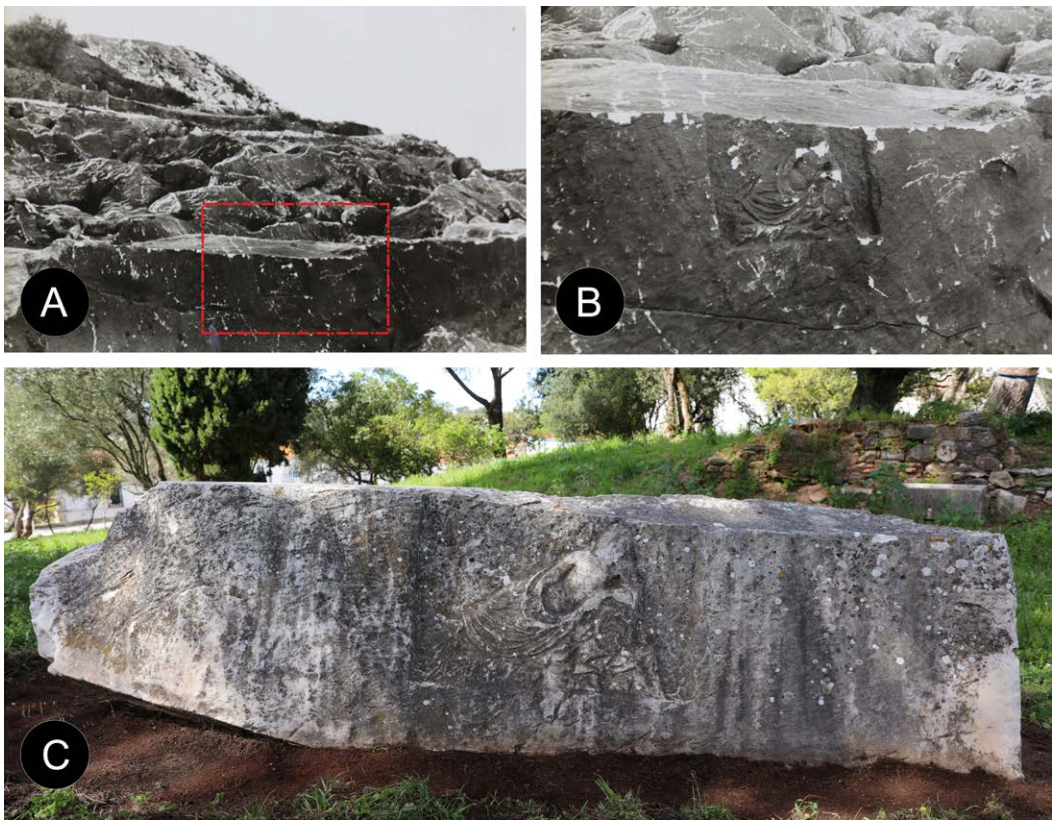

Figure 16. A bas-relief with a lying figure, possibly an aquatic deity, found *in situ* in the "VS" Solubema' s quarry (A) and (B) and then properly extracted and saved as a block is exhibited in the public garden of the castle of Vila Viçosa (C).

Figura 16. Un bajorrelieve con una figura yacente, posiblemente una deidad acuática, hallado *in situ* en la cantera de Solubema "VS" (A) y (B) y posteriormente extraído y conservado como bloque, se exhibe en el jardín público del castillo de Vila Viçosa (C).

Figure 17. Several archaeological pieces found in the Vigária quarries, now on display in the garden of Vila Viçosa Castle. The column at the top in the centre of the image comes from another location not far away, Herdade das Cagadinhas (locations on Fig. 3).

Figura 17. Varias piezas arqueológicas halladas en las canteras de Vigária, actualmente expuestas en el jardín del castillo de Vila Viçosa. La columna que aparece en la parte superior central de la imagen procede de otro yacimiento cercano, Herdade das Cagadinhas (ubicaciones en la Fig. 3).

Perhaps the main archaeological discovery in the Vigária sector is doubtlessly the massive statue of a *togato* with 2 m long by 80 cm wide who was left on site unfinished, probably for a natural fracture on its base (Fusco & Mañas, 2006: 34). This sculpture is preserved by the Solubema Company, belonging to its own collection of Roman pieces. Interestingly enough, a very similar in shape, proportion and size, yet properly finished statue, is known and exhibited in the archaeological museum of Merida in Spain (Fig. 18) which could lead us to believe that the Vigária area may have originated part of the white marble sculptures and architectural elements of Merida Theatre. Indeed, the provenance studies of sculptural pieces, including several *togato* pieces, from National Museum of Roman Art in Mérida based on petrographic and isotopic fingerprint of marbles (Lapuente *et al*., 2014) point the Estremoz Anticline as one of the main sources for the marble pieces of Mérida (see more on next section).

Figure 18. Unfinished *togato* found in a quarry in Herdade da Vigária (VK quarry?). Apparently, the sculpture began in the quarry itself but was abandoned because the stone did not meet the necessary requirements for its completion. For aesthetic comparison, a photograph of a more elaborate *togato* on display at the National Museum of Roman Art in Mérida, Spain, is attached (left). The museum *togato* is 1,76 m long and 0,74 m wide. If finished, the Vigária piece would have similar dimensions.

Figura 18. *Togato* inacabado hallado en una cantera de Herdade da Vigária (¿cantera VK?). Al parecer, la escultura se inició en la propia cantera, pero se abandonó porque la piedra no cumplía los requisitos necesarios para su finalización. Para una comparación estética, se adjunta (izquierda) una fotografía de un *togato* más elaborado expuesto en el Museo Nacional de Arte Romano de Mérida, España. El *togato* del museo mide 1,76 m de largo y 0,74 m de ancho. De haberse terminado, la pieza de Vigária tendría dimensiones similares.

5.2.4. Other archaeological findings

In addition to the aforementioned sectors, there are more traces of ancient quarrying in the other exploration centres, with this section being a tentative way to describe some of those examples (Fig. 19).

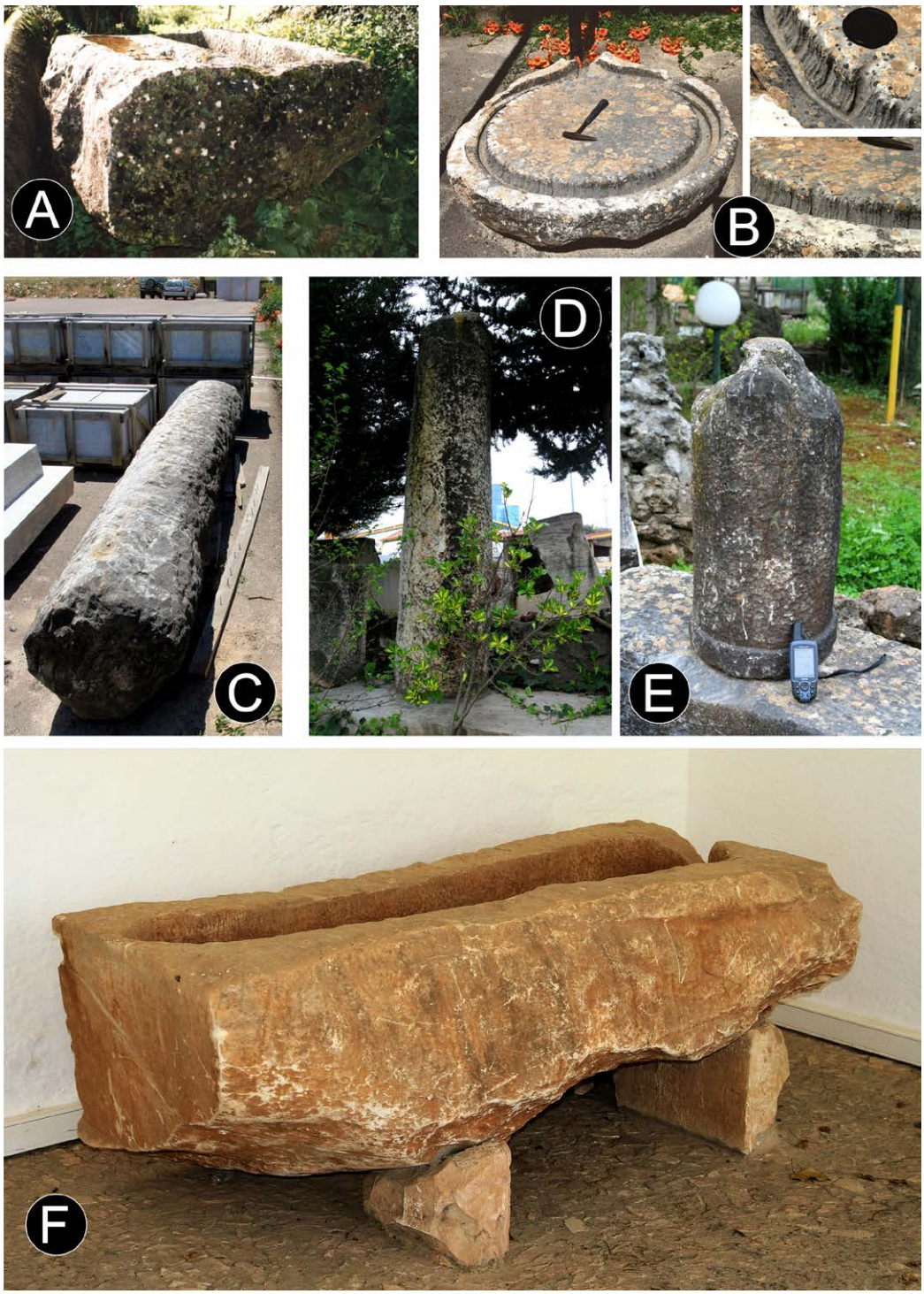

Figure 19. (A) unfinished double sarcophagus photographed in 1980 next to the boundary wall of "Monte do Olival", Glória, Estremoz. At that time, it was used as a watering trough for sheep; (B) olive oil press base; unfinished columns from Maroteira (C) and Lagoa quarries (D) and (E). These three columns were carved in dark blue marble (commercial variety called Ruivina); the Monte d' El-Rei sarcophagus is now on display at the Vila Viçosa Hunting and Archaeological Museum (F).

Figura 19. (A) Sarcófago doble sin terminar fotografiado en 1980 junto al muro perimetral de "Monte do Olival", Glória, Estremoz. En aquel entonces, se utilizaba como abrevadero para ovejas; (B) base de una prensa de aceite de oliva; columnas sin terminar de las canteras de Maroteira (C) y Lagoa (D) y (E). Estas tres columnas fueron talladas en mármol azul oscuro (variedad comercial llamada Ruivina); el sarcófago de Monte d' El-Rei se exhibe actualmente en el Museo Arqueológico y de Caza de Vila Viçosa (F).

Although the marbles of all the Estremoz Anticline are generally named Estremoz Marbles, this area does not have such significant evidence of marble exploration during Roman times. However, it should be emphasised that the ancient testimonies of ancient quarries reported by Justino Maciel (1997; 1998) in this area, as well as a series of old labour marks detected in the Regoto quarry (Estremoz) in the 1980s. The traces were detected "where pink, indigo, white marble was being extracted, at a depth of two or three metres under the sedimented soil", and there was also an "irregular block with two cavities carved in the shape of a sarcophagus", which had been found at the site and moved to Monte do Olival. Figure 19A shows the piece photographed in 1990 next to the boundary wall of "Monte do Olival", Glória, Estremoz, at that time used as a watering trough for sheep (Justino Maciel, 1988; Carneiro, 2019). Furthermore, in this area, one of the most intriguing archaeological sites was identified: one of the most important Roman hydraulic structures in *Hispania* was placed near Estremoz city (Tanque dos Mouros; Fig. 3; Quintela *et al*., 1986). Its function is still unknown (possible hydraulic tank for marble exploitation? Carneiro *et al*., 2022) and, as such, constitutes one of the sites to be investigated during future archaeological studies.

Another sarcophagus was also found in Monte d'El-Rei quarry (now displayed at the Vila Viçosa Hunting and Archaeological Museum; Fig. 19F). This sarcophagus, made in local pink marble, is one of the several loose testimonies and labour evidence found in Monte d 'El-Rei (also in Vila Viçosa municipality) (Justino Maciel, 1998; Carneiro, 2022 and included references).

An olive oil press base was found at the Marvisa company marble processing factory (Vila Viçosa). The location where it was first discovered is unknown, but the wear grooves left by the runoff of "rusty water" on the marble indicate that it had served its purpose (Fig. 19B). In the meantime, this piece was given to the Vila Viçosa City Council. In the same place, there was an unfinished column found in the company's quarry in Maroteira, Bencatel (Fig. 19C).

5.3. Estremoz marbles in historical buildings and in archaeological context: the consumption evidence

The industrial exploitation of marble from the Estremoz Anticline clearly began during Roman times. The stabilisation that followed the end of the Roman conquest of *Hispania* and the great building programme in the capital of the province of *Lusitania*, *Augusta Emerita* (nowadays Merida, founded circa 25 BC), promoted the local/regional search for raw materials for the "marmorisation" of *Emerita*. Therefore, the proximity to the capital of *Lusitania*, the relatively flat morphology of the territory and consequently, the easy transport of heavy stone loads and, obviously, the quality of this dimension stone and the extensive area for exploitation, promote the extensively use of Estremoz Anticline marble resources from the middle of the 1st century AD in this process of "marmorisation" of *Augusta Emerita* (e.g., Cisneros, 1988; Fusco & Mañas, 2006; Rodà de Llanza, 2012; Lapuente *et al*., 2014; Moreira, 2022). Indeed, the role of Estremoz Marbles in this process probably motivated the creation of an exploitation infrastructure, intending to feed the construction of the large public works, the implantation of accessibilities to this territory (several routes gave access to this region) and, possibly, a specific territorial management model.

The outstanding quality of this ornamental stone, the simple and massive regional and provincial accessibilities and the prestige associated with its massive application of Estremoz Marbles in the capital of the province, of which it can be highlight the use in architecture and sculpture of the most diverse temples and public buildings of *Emerita* (Fig. 20), promote the use of this exceptional raw material in the following centuries. Examples of this can be reported in its use in public programmes of several cities of *Lusitania* (e.g. *Ebora* [Fig. 20], *Ammaia*, *Olisipo*) (Cabral *et al*., 2001, 2004; Taelman *et al*., 2013) but also in other *Hispania* provinces, namely in *Baetica* (e.g., *Regina Turdulorum, Italica, Hispalis, Baelo Claudia*) and in *Tarraconensis* province (e.g., *Asturica Augusta, Caesaraugusta*) (Encarnação, 1987; Carredano *et al*., 2008; Royo *et al*., 2010; Cisneros *et al*., 2010-2011; Nogales *et al*., 2017; Beltran *et al*., 2018; Fernandes e Nogales, 2018; Ontiveros *et al*., 2024) (Fig. 21).

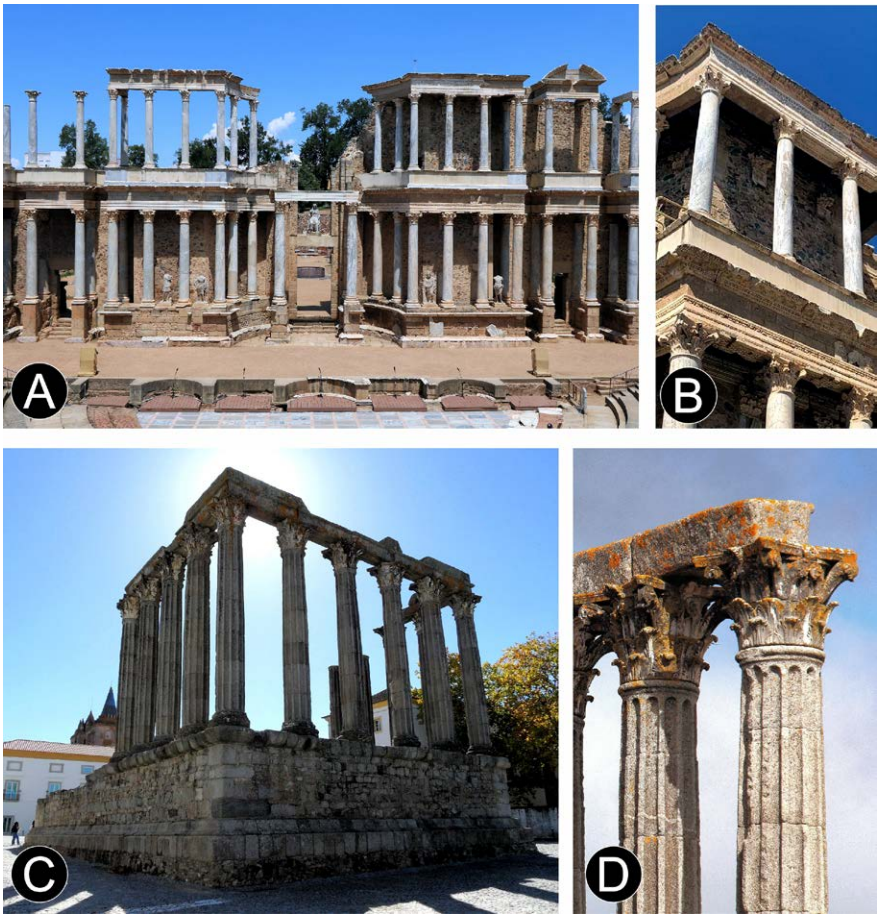

Figure 20. Use of the Estremoz Marbles in Roman public buildings: tiger skin marble used in the colonnade of *Emerita* Theatre (A and B) and with marble application in the Roman temple of Évora (C and D), namely in the base and capitals of the columns.

Figura 20. Uso de los mármoles de Estremoz en edificios públicos romanos: mármol piel de tigre utilizado en la columnata del Teatro *Emerita* (A y B) y con aplicación de mármol en el templo romano de Évora (C y D), concretamente en la base y los capiteles de las columnas.

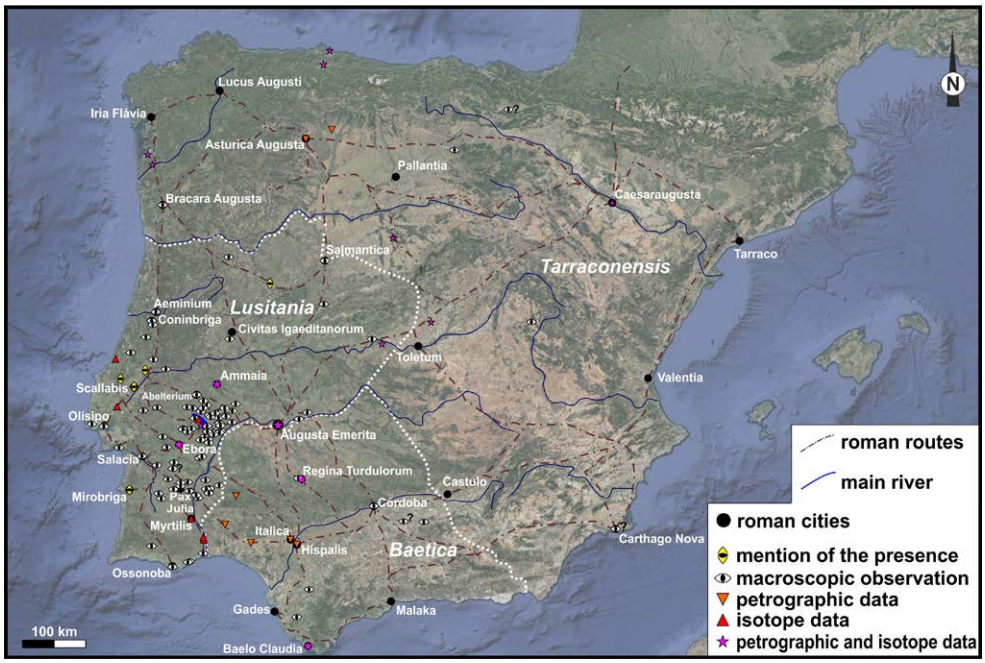

Figure 21. Spatial dispersion of marbles, with provenance attributed to the Estremoz Anticline, in consumption areas during the Roman times in the provinces of *Hispania* (see Moreira, 2022 for all the site's references).

Figura 21. Dispersión espacial de mármoles, con procedencia atribuida al Anticlinal de Estremoz, en áreas de consumo durante la época romana en las provincias de *Hispania* (véase Moreira, 2022 para todas las referencias del sitio).

However, the name of Estremoz Marble broke through the barriers of *Hispania*. Although their trade in Mediterranean lands of the Roman Empire is not proven, during the 2nd and 3rd centuries, the archaeometric data indicate their use in the public programs of Roman Morocco, namely in *Volubilis* (Antonelli *et al*., 2009). In *Thamusida* and *Banasa*, the archaeometric data (Origlia *et al*., 2011; Antonelli *et al*., 2015) do not totally exclude the presence of marbles from Estremoz Anticline (see Moreira, 2022 for a discussion), although the authors do not point out the presence of Estremoz Marbles in those Roman Cities.

After the middle of the 3rd century AD, there is a change in the consumers with the increase of private consumers. The construction of monumental *villae*, or luxurious rural residences, as well as the construction of religious tombs, sarcophagi and mausoleums and other Early Christian temples and structures extensively used the marble as part of the architectural ornamentation. During this period, Estremoz Marbles remain widely used, highlighting, as an example their use in several *villae* from *Lusitania* (e.g., Montinho das Laranjeiras, Alamo; Justino Maciel *et al*., 2006) and other provinces (Las Pizarras, Pérez *et al*., 2012), but also in religious architecture along *Hispania* (e.g., Pueblanueva, Carranque, Oviedo, Gijon; Vidal *et al*., 2017).

Therefore, the volume of exploited material which is necessary to feed all the Estremoz Marble demand during Roman times (Fig. 21) is huge, implying a significant industrial infrastructure of exploitation and a civil organisation.

6. CHALLENGES, VALORISATION PROPOSALS AND FINAL REMARKS

While some remains may have disappeared during the 20th century, resulting from the industrial quarrying activity, the abundance of testified ancient quarries, mostly located in Vigária for the light-coloured marbles and, Pardais and Lagoa for the grey and tiger skin typologies, is still very significant and deserves special attention. These sites seem to have worked contemporaneously, producing marbles that must have been used in the monumentalisation of *Augusta Emerita*, namely for the building of the Theatre, but also in several other monuments and Roman cities of *Lusitania* and other *Hispania* provinces.

The classification of Estremoz Marble as a Global Heritage Stone Resource in 2018 (e.g., Lopes & Martins, 2015, 2018) by IUGS was obviously based on its historical heritage, with 2000 years of documented exploitation. In a holistic view of the nature of this ornamental stone and considering the inevitability of the exploitation of this geological resource in present days, this recognition is the greatest source of wealth for the region, valorising this raw material. However, there is a lot of work to do, to dignify the history and the touristic potential of this natural stone, thus promoting the value and the social and economic importance of this industrial sector near the civil society, in the meantime that promote the sustainability exploitation and the good environmental and rehabilitation practices.

For this, it is totally necessary to find operational synergies between all the entities, namely the local and national governments, schools, industrial companies and association to preserve, valorise, publicise and enhance the value of archaeological, social and constructed heritage of all this region, which is totally grounded in the marble industry. The main industrial, political and social challenges identified were:

1. The necessity to undertake a significant geo-archaeological regional campaign of exploration to find additional remains of ancient exploitation, applying not only the traditional field techniques, but also new indirect methods such as geophysics and remote sensing techniques (Fig. 22).

2. Geo-archaeological follow-up of new superficial works, including local superficial archaeological prospection and preliminary detection of buried ancient quarries or other archaeological findings using indirect methods, namely geophysical methods like georadar. This protocol intends to prevent the destruction of unknown archaeological occurrences.

3. It is central to raise awareness among all the companies and industrials, but also the civil society, of the importance of the preservation of those archaeological artifacts as a differentiating element which valorises the industrial history of marble in the Estremoz Anticline.

4. Enhance the value of the existing industrial and archaeological heritage around the thematic of “2000 years of exploitation of a Global Heritage Stone Resource” promoting workshops, documentaries and exhibitions, but also an international scale interpretive centre in this region or some local scale centres enhancing the history of marble exploitation in all the Estremoz Anticline municipalities.

5. Promote the geo-archaeological knowledge about the use of this ornamental stone during Roman times, but also during medieval, modern and contemporary times, thus evaluating the global dispersion of this raw material. These studies should also be accompanied by industrial-targeted investigation promoting the well characterisation of physical and chemical properties of all the typologies of Estremoz Marbles and the best use of this georesource and the reduction of waste resulting from extractive activities.

6. Creation of a geo-archaeological virtual library including the geological, geochemical and physical properties of all the typologies of Estremoz Marbles, and the archaeological information about Roman exploitation, including the 3D scanning of the known archaeological pieces.

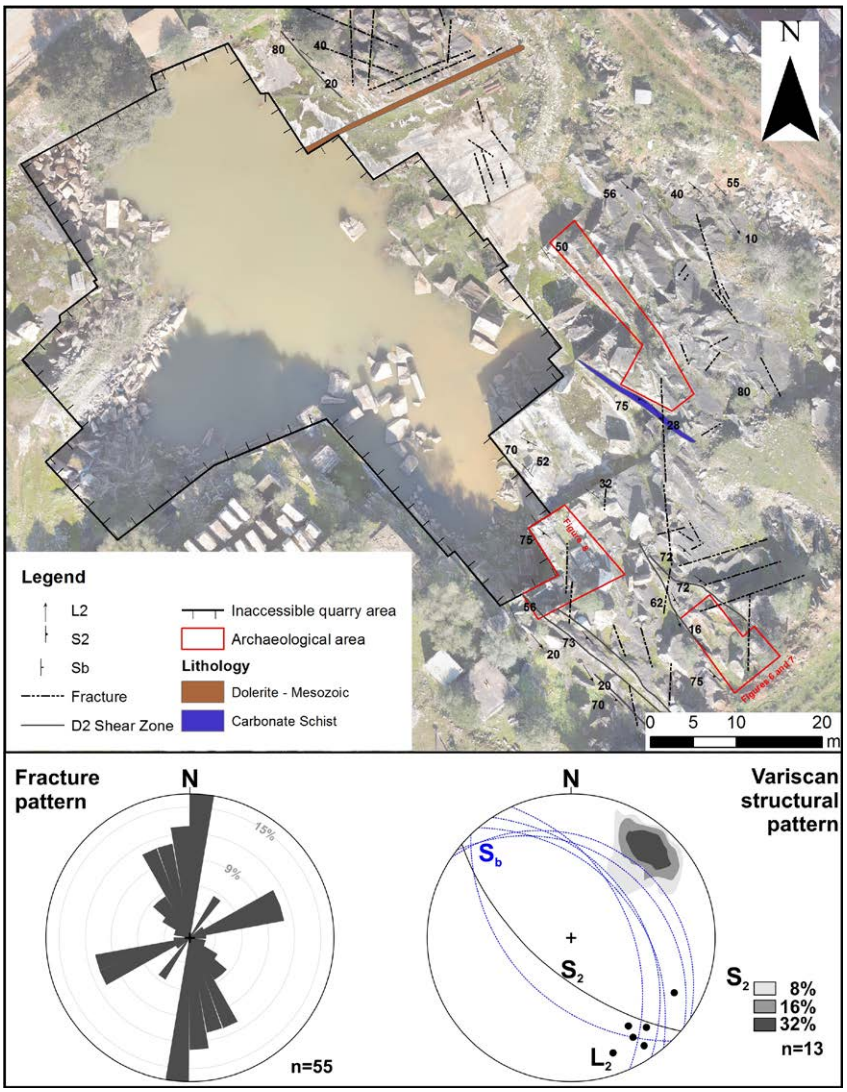

Figure 22. High-resolution image obtained by processing 85 photographs taken by drone. Although this is a 2D image, it perfectly shows the main directions of discontinuities present in the quarry and which condition the obtaining of blocks for commercial purposes. Note that this structural control of exploitation was already considered in the development of the historic quarry (see also Figure 8 for an explanation).

Figura 22. Imagen de alta resolución obtenida mediante el procesamiento de 85 fotografías tomadas con un dron. Si bien se trata de una imagen bidimensional, muestra con precisión las principales direcciones de discontinuidad presentes en la cantera, las cuales condicionan la obtención de bloques para fines comerciales. Cabe destacar que este control estructural de la explotación ya se consideró durante el desarrollo de la cantera histórica (véase también la Figura 8 para una explicación).

With respect to the Roman organisation of the Estremoz Anticline territory, there are unsolved questions that need to be answered:

- Identification of the resource: preliminary to any exploitation, the marble resources of the region should have been identified during the Roman campaign, which is normal since the Roman conquest of *Hispania* took 200 years; naturally, there was in-depth knowledge of local resources. While the role of "procuratores" in the Roman army is well known for the mapping of the metallic resources of *Hispania* and *Lusitania*, it has also been documented in the marble resources of the region (Carneiro, 2019). The scale of the Roman marble exploitation in our area displays a remarkable knowledge of the local lithological facies preliminary to the quarrying in Alentejo (and going as far as Serpa and Viana do Alentejo area for the green marbles, and Trigaches, for grey coarse texture marbles).

- Workforce: exploiting marble was not a skill that a local workforce could have mastered in the earlier stage of the exploitation. This implies that skilled workers were probably brought from elsewhere in the empire and installed on the site of the Lusitanian quarries at least for the first generation. Due to the significant distance between the Pardais, Lagoa and Vigária locations (7km) and the simultaneity of the exploitation, several skilled teams had to run contemporaneously to supply the job site. This implies that the number of these workers must have been significant since the very beginning of the extraction works. Similar implantation of foreigners should have left traces of settlements (housing, farms, furnace for the tools, funerary ground, etc.), which so far seems not to have been documented in this area.

In the present moment, one of the most significant valorisation proposals is the preservation and outdoor musealisation of the Marmoz quarry in Lagoa Sector (Fig. 22), which presents not only archaeological interest due to ancient (probably Roman) quarrying remains, but also evidence of multitemporal phases of contemporary exploitation. Indeed, there are still scattered throughout the cavity stays related to industrial archaeology from the 50's to the 90's of the 20th century, namely drilling columns, turnbuckles and pulleys and various coils and fragments of helical wire, steel wedges and Derrick crane support structures, however, removed. Different methods of dismantling the massif are also present, from the oldest ones related to the Roman Period, as mentioned above, to dismantling by continuous drilling using compressed air hammers, cutting with helical wire (cutting with siliceous sand), denounced by the characteristic wavy grooves that it originates and the most recent clean cut with diamond wire.

But the heritage interest of the Marmoz quarry is not limited to archaeological remains. In this quarry, it is also possible to see and discuss at quarry scale the geological structures that shaped the Estremoz Anticline. For example, in marbles, there are variations in textures and colours with angular unconformities and lateral facies variations that refer to the geodynamics of the sedimentary basin prior to metamorphism and Variscan deformation. Interstratified with the marbles, there are levels of green schist interpreted as levels of volcanic ash. It is even possible to see a gradient from pink to white colours in the marbles upon contact with these levels, suggesting a geochemical gradient migration during regional metamorphism from the metavolcanics. As regarding regional tectonics, both two phases of ductile deformation are present here: (1) the first one generates folds with a sub-horizontal axial plane in an East-West direction and vergence to the North, which is observed in one of the exploitation fronts in a NW-SE direction; and (2) the second phase, responsible for the NW-SE general orientation of the Estremoz Anticline and materialised by regional banding with this orientation, defines open folds with an axial plane inclined at around 70° to the SW. All these ductile structures are cut by brittle sub vertical fault systems, with emphasis on the one with conjoined pairs: N-S and N60°E, the latter one with occasional installation of a late dolerite dyke with approximately one metre thick (Fig. 22). Also here, it is possible to see the late dolomitisation process (locally known as owl's eye texture), the karst pattern of the marble caused by their dissolution, and the *terra rossa* soil resulting from the *in-situ* concentration of iron oxides and other insoluble minerals.

Another feature that deserves highlighting is related to the fauna and flora present. Normally these quarries function as a refuge for wildlife (Germano, 2013; Germano *et al.*, 2014) and this one is no exception as can be seen both through direct observation of the birdlife, reptiles, amphibians and

mammals, by the sounds they produce and also by the traces of movement they leave in the soil covered by fine dust and/or in the footprints preserved in pools of water with clay.

The aforementioned aspects justify continue to work in synergy with Marmoz company, that recognises the heritage and historical value of this space outweighed the commercial value of the blocks that could be extracted from here and, at our request, since 2005, chose to preserve this quarry, at all exceptional levels, even more so because, as far as is known today, it constitutes the best-preserved example of a historic quarry on the Estremoz Anticline.

Another valorisation proposal is related to the creation of an expository space, which includes most of the Roman archaeological findings that are scattered in several parts, thus valuing the Roman archaeological-industrial ensemble found in the Estremoz Anticline municipalities. If it is not possible, the focus should be on the Vila Viçosa municipality, where the most testimonies were found. This expository space should include not only the architectonic and sculptural pieces found but also the dismantled quarry from the Lagoa sector previously described.

Supplementary information ↑

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Supplementary material

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Data availability

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Authorship contribution statement

Luís Lopes: Conceptualisation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Photographs, Image editing, Writing – review & editing.

Noel Moreira: Conceptualisation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Image editing, Writing – review & editing.

Gil Vilarinho: Investigation, Methodology, Writing – original draft, Writing – review & editing.

Ruben Martins: Photographs, Writing – original draft, Writing – review & editing.

André Carneiro: Investigation, Methodology, Writing – original draft, Writing – review & editing.

Francis Kezirian: Formal analysis, Funding acquisition, Investigation, Writing – original draft.

Marcelo Silva: Writing – original draft, Writing – review & editing, Drone Operator, Image Acquisition and Processing.

Pedro Nogueira: Writing – original draft, Funding acquisition, Drone Operator, Image Acquisition and Processing.

Competing interests

The authors of this article declare that they have no financial, professional, or personal conflicts of interest that could have inappropriately influenced this work.

Statement on the use of Artificial Intelligence

Not applicable.

REFERENCES

Adam, J.-P. (1989). Translated by Anthony Mathews; Roman Building, materials and Techniques; Routledge, London and New York, p. 735.

Alarcão, J. (2004). Introdução ao Estudo da Tecnologia Romana; design José Luís Madeira. Coimbra: Instituto de Arqueologia - Faculdade de Letras da Universidade de Coimbra, 2004. - 195, [2] p.: il.; 25 cm. - (Cadernos de Arqueologia e arte, 7). ISBN 972-9004-18-8.

Alchermes, J. (1994). "Spolia in roman cities of the late empire: legislative rationales and architectural reuse", DOP, 48, p. 167-178.

Antonelli, F., Lapuente, M. P, Dessandier, D. & Kamel, S. (2015). Petrographic characterization and provenance determination of the crystalline marbles used in the Roman City of Banasa (Morocco): new data on the import of Iberian Marble in Roman North Africa. Archaeometry, 57(3), 405-425. DOI: 10.1111/arcm.12099.

Antonelli, F., Lazzarini, L., Cancelliere, S. & Dessandier, D. (2009). Volubilis (Meknes, Morocco): Archaeometric study of the white and coloured marbles imported in the Roman age. Journal of Cultural Heritage, 10, 116-123. DOI:10.1016/j.culher.2008.04.006.

Bairrão Oleiro, J. M. (1966). Achado de dois sarcófagos numa pedreira em Pardais, Parecer, Lisboa, Junta Nacional de Educação.

Beltrán Fortes, J., Ontiveros, E., Loza, M. L., Rodríguez, O. & Taylor, R. (2018). 'Marmora' de procedencia hispana en '*Baelo Claudia*' (Bolonia, Tarifa, Cádiz)", in Beltrán, J., Loza, M.L., Ontiveros, E. (Eds.), *Marmora Baeticae*: usos de materiales pétreos en la Bética romana: estudios arqueológicos y análisis arqueométricos. Sevilla: Universidad de Sevilla, 17-37.

Cabral, J. M., Vieira, M. C. R., Carreira, P. M., Figueiredo, M. O., Pena, T. P. & Tavares, A. (1992). Preliminary study on the isotopic and chemical characterization of marbles from Alto Alentejo (Portugal). In: Waelkens, M., Herz, N., Moens, L. (Eds.), Ancient Stones: Quarrying, Trade and Provenance e Interdisciplinary Studies on Stones and Stone Technology in Europe and Near East from the Prehistoric to the Early Christian Period. Leuven University Press. Leuven. 191-198.

Cabral, J. M. P., Maciel, M. J., Lopes, L., Lopes, J. M. C., Marques, A. P. V., Mustra, C. O. & Carreira, P. M. (2001). Petrographic and isotopic characterization of marble from the Estremoz Anticline: its application in identifying the sources of Roman works of art, Journal of Iberian Archaeology, 3, 121-128.

Cabral, J. M. P., Mustra, C. O. & Hauschild, T. (2004). A proveniência do mármore dos capitéis do Templo Romano de Évora. Conimbriga 43: 171-177. DOI: 10.14195/1647-8657_43_7

Carneiro, A., Trapero, P. & Moreira, N. (2022). A exploração do mármore do Anticlinal de Estremoz em época romana: discussão dos resultados e perspetivas de futuro. In: Carneiro, A., Soares, C.M., Grilo, F., Serrão, V., (coord.). Mármore: 2000 anos de História, Volume 3 – Contributo dos Mármores do Alentejo para a afirmação das artes. PHIM – Património e História da Indústria dos Mármores, Almedina, Coimbra, 143-158.

Carneiro, A. (2014). Lugares, tempos e pessoas: povoamento rural romano no Alto Alentejo - vol. I. Imprensa da Universidade de Coimbra, Coimbra. ISBN: 978-989-26-0831-0.

Carneiro, A. (2019). A exploração do mármore do Anticlinal de Estremoz: extração, consumo e organização, In Serrão, V., Moura, C. e Carneiro, A. (Coords.) *Mármore. 2000 anos de história*, Lisboa: Theva: 55 -120.

Carneiro, A. (2022). Os mármores do Anticlinal: logísticas de extracção e transporte, In Carneiro, A., Moura Soares, C., Grilo, F. e Serrão, V. (Coords.) *Mármore. 2000 anos de história: Volume III – Contributo dos mármores do Alentejo para a afirmação das artes*, Edições Almedina: 121-142.

Carredano, F. A., Beltrán, J. & González Acuña, D. (2008). "*Marmora de Hispalis*. Estudio de los materiales pétreos recuperados en las excavaciones arqueológicas de 'La Encarnación' (Sevilla)", in Nogales Basarrate, Trinidad, e José Beltrán Fortes (Eds.), *Marmora hispana*: explotación y uso de los materiales pétreos en la Hispania Romana (Hispania Antigua. Serie Arqueológica, 2). Roma: «L'Erma» di Bretschneider, 213-229. ISBN: 978-88-8265-453-5.

Casal Moura, A. (Coord.) (2007). Mármores e Calcários Ornamentais de Portugal. INETI (National Institute of Engineering, Technology and Innovation). Lisboa.

Cisneros Cunchillos, M. (1988). Mármoles hispanos: su empleo n la España romana. Universidad Zaragoza, 199p. ISBN: 978-84-600-7010-8.

Cisneros Cunchillos, M., Gisbert Aguillar, J. & Somovilla de Miguel, I. A. (2010-2011). El uso del mármol en la arquitectura de Asturica Augusta. Anales de Arqueología Cordobesa, 21-22, 93-126.

Conti, A. & Bessi, I. (1996). Il Marmo…Ieri e Oggi. Storia fotografica della lavorazione del marmo. Edizione Società Editrici Apuana, Massa, Carrara; p. 252.

Del Soldato, M. & Pintus, S. (1985). Studio geologico-storico delle attività e delle tecniche estrattive nella Liguria Orientale (area compresa fra Genova e La Spezia), Memorie Accademia Lunigianese, XLV-XLII. p. 138.

Dias, R., Ribeiro, A., Romão, J., Coke, C. & Moreira, N. (2016). A review of the Arcuate Structures in the Iberian Variscides; Constraints and Genetic Models. Tectonophysics, 681C, 170-194. DOI: 10.1016/j.tecto.2016.04.011.

Durão, L. (2017). "O Paço Ducal de Vila Viçosa – suas características portuguesas", Re-Dispersos de Arquitectura.

Encarnação, J. (1987). "Religião e cultura na Évora dos romanos". Separata da Revista A Cidade de Évora, 5, p. 5-19.

Fant, C. (1988). "The Roman emperors in the marble business: capitalists, middlemen or philanthropists", Dordrecht, p. 147-158.

Fernandes, L. & Nogales, T. (2018). "Teatro Romano de Olisipo: programas decorativos teatrales de Lusitania", in Márquez, Carlos (ed.). Actas de la VIII Reunión Internacional de Escultura Romana en Hispania. Córdoba: Universidad de Córdoba y Baena, 432-455.

Fusco, A. & Mañas, I. R. (2006). Mármoles de Lusitania. Edição: Museo Nacional de Arte Romano, Mérida, España. ISBN: 100956535, p. 49.

Germano, D. L. C. (2013). Análise da evolução da recuperação ecológica em pedreiras de mármore inativas no Anticlinal de Estremoz: Avifauna, Flora e Vegetação. Tese de Mestrado em Qualidade e Gestão do Ambiente (especialidade em Ecologia e Gestão Ambiental). Universidade de Évora, Évora. 169 p.

Germano, D., Lopes, L., Pinto Gomes, C., Santos, A. P. & Martins, R. (2014). O impacte das pedreiras inactivas na fauna, flora e vegetação da zona dos mármores: problema ou benefício? Callipole – Revista de Cultura n.º 21, pp. 161-183, Vila Viçosa.

Gomes Silva, C. (1989). Mármores da região de Estremoz-Borba-Vila Viçosa. Caracterização minero-petrográfica, geoquímica e geomecânica. Contribuição para o conhecimento da sua alterabilidade, fracturação e blocometria, IST, Lisboa, 136 p.

Gonçalves, F. (1970). Contribuição para o conhecimento geológico dos mármores de Estremoz. Est. Notas e Trabalhos do SFM. Porto. 20:1-2, pp. 201-209.

Gonçalves, F. (1972). Observações sobre o anticlinório de Estremoz. Alguns aspectos geológico-económicos dos mármores, Est. Not. Trab., (22) 1-2, 121-132 (Matérias-primas minerais não metálicas, nº 17). Porto: Serviço de Fomento Mineiro.

Gonçalves, F. & Coelho, A. V. P. (1974). Carta geológica de Portugal na esc. 1/50 000 Notícia explicativa da folha 36-B, (Estremoz) - S.G.P. Lisboa. 64 p.

Gonçalves, F. & Oliveira, V. (1986). Alguns aspectos do Precâmbrico da Zona de Ossa-Morena em Portugal. O Proterozóico Superior de Estremoz. Memórias da Academia de Ciências de Lisboa 27, 111-117.

Gomes, E. M. C. & Fonseca, P. E. (2006). Eventos metamórfico/metassomáticos tardi-variscos na região de Alvito (Alentejo, sul de Portugal). Cadernos Lab. Xeolóxico de Laxe, 31, 67-85.

Gutiérrez García, M. (2011). The exploitation of local stone in Roman times: the case of north-eastern Spain. World Archaeology, 43(2), 318-341.

Harrell, J. (2014). Stone in Ancient Egypt, In Selin, H. (eds.) Encyclopaedia of the History of Science, Technology, and Medicine in Non-Western Cultures, Dordrecht, Springer: 1-8. DOI: 10.1007/978-94-007-3934-5_9176-2.

Justino Maciel, M. (1988). Arte romana e pedreiras de mármore na Lusitânia: novos caminhos de investigação. Revista da Faculdade de Ciências Sociais e Humanas, 11, 233-245.

Justino Maciel, M. (1997). Évora na Antigüidade Tardia, in: Afonso de Carvalho et.al., Évora, História e Imaginário, Ataegina - Associação de Produções Culturais, Évora.

Justino Maciel, M., Cabral, J. M. P. & Nunes, D. (2006). A estátua de Apolo na Villa do Álamo (Museu Nacional de Arqueologia). O Arqueólogo Português IV Série – 24, 349-367.

Justino Maciel, M. & Coutinho, H. (1990). A utilização dos mármores em Portugal na época Romana. Ensaio de uma metodologia de estudo. Estudos em homenagem a João Francisco Marques vol. II, pág. 81-86. https://ler.letras.up.pt/uploads/ficheiros/2860.pdf. Texto apresentado e desenvolvido em 28 de Abril de 1990, no II Colóquio de Arqueologia de Viseu.

Karaglou, K. (2016). Trends in Hellenistic sculpture, In Picón, C. and Hemingway, S. (eds.) Pergamon and the Hellenistic Kingdoms of the Ancient World, The Metropolitan Museum of Art, New York: 62-69.

Lapuente, M. P. (1995). Mineralogical, petrographical and geochemical characterization of white marbles from Hispania", In Y. Maniatis, N. Herz y Y. Basiakos (eds.), ASMOSIA III. The Study of Marble and Other Stones Used in Antiquity: 151-160. Athens (1993), London, Archetype Books. DOI: 10.13140/RG.2.1.1854.4168.

Lapuente, M. P. & Turi, B. (1995). Marbles from Portugal: petrographic and isotopic characterization. Science and Technology for Cultural Heritage, 4, 33-42.

Lapuente, M. P. & Blanc, P. (2002). Marbles from Hispania: scientific approach based on cathodoluminescence. In: J. Herrmann, Jr. N. Herz, R. Newman (eds.) Asmosia 5. Interdisciplinary Studies on ancient stone, Archetype Pub, London, 143-151.

Lapuente, P., Turi, B. & Blanc, P. (2000). Marbles from Roman Hispania: stable isotope and cathodoluminescence characterization. Applied Geochemistry, 15, 1469-1493.

Lapuente, P., Nogales-Basarrate, T., Royo, H. & Brilli, M. (2014). White marble sculptures from the National Museum of Roman Art (Mérida, Spain): sources of local and imported marbles. European Journal of Mineralogy, 26, 333-354. DOI: 10.1127/0935-1221/2014/0026-2369.

Laranjeira, V., Ribeiro, J., Moreira, N., Nogueira, P., Mendonça Filho, J. G. & Flores, D. (2023). Petrographic and geochemical characterization of organic matter in Precambrian black shales from Ossa-Morena Zone, South of Portugal. In: Chaminé, H.I., Fernandes, J.A. (Eds.), Advances in Geoengineering, Geotechnologies, and Geoenvironment for Earth Systems and Sustainable Georesources Management. Advances in Science, Technology & Innovation. Springer ASTI Series, 97-101. DOI: 10.1007/978-3-031-25986-9_16.

Lopes, J. L. (2003). Contribuição para o conhecimento Tectono-Estratigráfico do Nordeste Alentejano, transversal Terena-Elvas. Implicações económicas no aproveitamento de rochas ornamentais existentes na região (Mármores e Granitos). PhD Thesis (unpublished). Universidade de Évora. 568p.

Lopes, J. L. (2007). O triângulo do mármore: estudo geológico. Monumentos, 27, 6-15.

Lopes, J. L., Carrilho Lopes, J. C., Cabral, J. P. & Sarantopoulos, P. (2000). Caracterização Petrográfica dos Monumentos Romanos de Évora. Revista "Cidade de Évora" II Série, Nº4: 129-142.

Lopes, L. & Martins, R. (2015). Global Heritage Stone: Estremoz Marbles, Portugal. From: Pereira, D., Marker, B. R., Kramar, S., Cooper, B. J. & Schouenborg, B. E. (eds) Global Heritage Stone: Towards International Recognition of Building and Ornamental Stones. Geological Society, London, Special Publications, 407, http://dx.doi.org/10.1144/SP407.10.

Lopes, L. & Martins, R. (2018). Reconhecimento do mármore de Estremoz como pedra património mundial. Callipole – Revista de Cultura n.º 25 – 2018, pp. 293-310. Vila Viçosa.

Lopes, L., Beltrán, J., Ontiveros, E., Moreira, N., Loza, M. L. & Carneiro, A. (2024). Almadén de la Plata marble: a Heritage Stone Proposal, EGU General Assembly 2024, Vienna, Austria, 14-19 Apr 2024, EGU24-13508, https://doi.org/10.5194/egusphere-egu24-13508, 2024.

Mañas, I. & Fusco A. (2008). Canteras de Lusitania. Un análisis arqueológico. In: Nogales, T., Beltrán, J. (Eds), Marmora Hispania: explotación y uso de los materiales pétreos en la Hispania Romana, Rome, 481-522.

Marano, Y. (2016). The circulation of marble in the Adriatic Sea at the time of Justinian, London, p. 111-132.

Martins, R. (1996). Aplicações industriais de natas resultantes da indústria transformadora de rochas ornamentais carbonatadas. MSc Thesis (unpublished), Universidade de Aveiro, 1996

Mata, J. & Munhá, J. (1985). Geochemistry of mafic metavolcanic rocks from the Estremoz Region (South Central Portugal). Comun. Serv. Geol. Portugal, 71(2), 175-185.

Menningen, J., Siegesmund, S., Lopes, L., Martins, R. V. & Sousa, L. (2018). The Estremoz marbles: an updated summary on the geological, mineralogical and rock physical characteristics. Environ. Earth Sci., 77, 191. https://doi.org/10.1007/s12665-018-7328-3.

Morbidelli, P., Tucci, P., Imperatori, C., Polvorinos, A., Preite Martinez, M., Azzaro, E. & Hernandez, M. J. (2007). Roman quarries of the Iberian Peninsula: “Anasol” and “Anasol”-type. Eur. J. Mineral., 19, 125-135. DOI: 10.1127/0935-1221/2007/0019-0125.

Moreira, J. & Vintém, C. (Coord) (1997). Carta Geológica do Anticlinal de Estremoz, escala 1:25.000. Dept. Prospecção de Rochas e Minerais Não Metálicos, Instituto Geológico e Mineiro, Lisboa.

Moreira, N. (2017). “Evolução geodinâmica dos sectores setentrionais da Zona de Ossa-Morena no contexto do Varisco Ibérico”. PhD Thesis, Universidade de Évora, 2017. http://hdl.handle.net/10174/22620.

Moreira, N. (2022). Difusão dos Mármores do Anticlinal de Estremoz no Império Romano; até onde se reporta a sua expansão? *In* Mármore: 2000 anos de História, Volume 3 – Contributo dos Mármores do Alentejo para a afirmação das artes, 69-109. Almedina.

Moreira, N., Araújo, A., Pedro, J.C. & Dias, R. (2014). Evolução geodinâmica da Zona de Ossa-Morena no contexto do SW Ibérico durante o Ciclo Varisco. Comunicações Geológicas, 101 (Especial I), 275-278.

Moreira, N. & Lopes, L. (2019). Caracterização dos Mármores de Estremoz no contexto dos Mármores da Antiguidade Clássica da Zona de Ossa-Morena. In: Serrão, V., Soares, C.M., Carneiro, A. (coord.). PHIM – Património e História da Indústria dos Mármores: Mármore: 2000 anos de História. Volume 1: Da Antiguidade à idade Moderna. Theya Editores, Lisboa, 13-54. ISBN: 978-989-99164-3-2.

Moreira, N., Pedro, J., Lopes, L., Carneiro, A., Mourinha, N., Araújo, A., Santos, J. F. (2020). The Ossa-Morena Marbles used in Classical Antiquity: review of their petrographic features and isotopic data. Comunicações Geológicas, 107 (Especial II) (XII CIG), 81-89.

Moreira, N., Pedro, J., Santos, J. F., Araújo, A., Dias, R., Ribeiro, S., Romão, J. & Mirão, J. (2019). 87Sr/86Sr applied to age discrimination of the Palaeozoic carbonates of the Ossa-Morena Zone (SW Iberia Variscides). International Journal of Earth Sciences, 108(3), 963-987. DOI: 10.1007/s00531-019-01688-9.

Mourinha, N. & Moreira, N. (2019). Património edificado no Triângulo do Mármore; evidências para a utilização contínua do Mármore de Estremoz desde a Época Medieval à Idade Contemporânea. In: Arqueologia 3.0 – II. Comunicação, Divulgação e Socialização da Arqueologia. Fundação da Casa de Bragança, 171-206. ISBN: 978-972-9195-53-2.

Nogales Basarrate, T., Lapuente, P. & Rodà, I. (2017). Dos nuevos retratos de Caesar Augusta (Zaragoza), Revue Archéologique de l’Est, 44e, 261-270.

Oliveira, J. T., Oliveira, V. & Piçarra, J. M. (1991). Traços gerais da evolução tectono-estratigráfica da Zona de Ossa-Morena, em Portugal: síntese crítica do estado actual dos conhecimentos. Comun. Serv. Geol. Portugal, 77, 3-26.

ONTIVEROS ORTEGA, E., MOREIRA, N., LOPES, L., LOZA AZUAGA, M. L., BELTRÁN FORTES, J. (2024). Marmora del anfiteatro de Itálica. Identificación arqueométrica: un ejemplo del uso de los mármoles de Lusitania y Baetica en época romana imperial. In: BELTRÁN FORTES, J. (coord.) Edificios de espectáculos romanos de la Bética: anfiteatros y circos. Carmona, Itálica y Écija, Sevilla, Editorial Universidad de Sevilla, 245-262.

Ontiveros, E., Beltrán Fortes, J. & Loza, M. L. (2020). Estudio arqueométrico del soporte marmóreo de una escultura de Livia hallada en la ciudad romana de Asido (Medina Sidonia, Cádiz). Ge-Conservacion, 18, 108-122. https://doi.org/10.37558/gec.v18i1.750.

Origlia, F., Gliozzo, E., Meccheri, M., Spangenberg, J. E., Turbanti Memmi, I. & Papi, E. (2011). Mineralogical, petrographic and geochemical characterisation of white and coloured Iberian marbles in the context of the provenancing of some artefacts from Thamusida (Kenitra, Morocco). Eur. J. Mineral., 23, 857-869. DOI: 10.1127/0935-1221/2011/0023-2145.

Padilla-Monge, A. (2018). "Pagus Marmorariensis, mons Mariorum, statio serrariorum Augustorum y canteras de Almadén de la Plata. Algunas precisiones". Boletín del Museo Arqueológico Nacional, 37, 119-129.

Pereira, M. F., Solá, R., Chichorro, M., Lopes, L., Gerdes, A. & Silva, J. B. (2012). North-Gondwana assembly, break-up and paleogeography: U–Pb isotope evidence from detrital and igneous zircons of Ediacaran and Cambrian rocks of SW Iberia. Gondwana Research, 22, 866-881. http://dx.doi.org/10.1016/j.gr.2012.02.010.

Perez, A. A., Olivé, M. M. & Llanza, I. R. (1998). La Aplicación del Metodo de Isotopos Estables a Mármoles Explotados en Época Romana en la mitad sur de la Península Ibérica. AEspA, 71, 103-112.

Pérez, C., Reyes, O., Rodá, I., Álvarez, A., Gutiérrez García-M., A., Domènech, A. & Royo, H. (2012). Use of marmora in the ornamental program of Las Pizarras roman site (ancient Cauca, Segovia, Spain). In: A. Gutiérrez García-M., P. Lapuente e I. Rodá (eds.), Interdisciplinary Studies on Ancient Stone. Proceedings of the IX Association for the Study of Marbles and Other Stones in Antiquity (ASMOSIA) Conference. Institut Català d'Arqueologia Clàssica. Tarragona, 151-160.

Piçarra, J. M. (2000). Estudo estratigráfico do sector de Estremoz-Barrancos, Zona de Ossa Morena, Portugal. Vol. I – Litoestratigrafia do intervalo Câmbrico médio?-Devónico inferior, Vol. II - Bioestratigrafia do intervalo Ordovícico-Devónico inferior. Tese de Doutoramento (não publicada). Universidade de Évora.

Quintela, A. C., Cardoso, J. L. & Mascarenhas, J. M. (1986). Aproveitamentos hidráulicos romanos a Sul do Tejo: contribuição para a sua inventariação e caracterização. Direcção Geral dos Recursos e Aproveitamento Hidráulicos.

Rodà de Llanza, I. (2012). El comercio de los mármoles en Hispania. Historia Antiqua, 21, 85-91.

Roseiro, J., Moreira, N., Andrade, L., Nogueira, P., De Oliveira, D., Eguiluz, L., Mirão, J., Moita, P., Santos, J. F., Ribeiro, S. & Pedro, J. (2025). Contact metamorphism and dolomitization overprint on Cambrian carbonates from the Ossa-Morena Zone (SW Iberian Massif): implications to Sr-chronology of carbonate rocks. International Journal of Earth Sciences, 114, 193-217. DOI: 10.1007/s00531-024-02476-w.

Royo, H., Lapuente M. P. & Nogales-Basarrate, T. (2010). Primeros resultados arqueométricos en el estudio de los programas estatuarios del Foro de Regina (Provincia Baetica). In: Saiz Carrasco, M. E., López Romero, R., Cano Díaz-Tendero, M. A., Calvo García, J. C. (eds.), Actas VIII Congreso Ibérico de Arqueometría, Teruel, 147-155.

Russell, B. (2013). Gazetteer of Stone Quarries in the Roman World. Version 1.0 (Oxford Roman Economy Projet). Available in: http://www.romaneconomy.ox.ac.uk/ - accessed on June 24, 2024.

Saa, M. de (1956-1967). As grandes vias da Lusitânia: O itinerário de Antonino Pio. Lisboa, Ed. do Autor, 6 volumes.

Silva, J. M. & Camarinhas, M. V. F. (1957). Calcários cristalinos de Vila Viçosa – Souzel. Estudos, Notas e Trabalhos do Serviço de Fomento Mineiro, XII, 66-139.

Suetonius. Lives of the Caesars, Volume I: Julius. Augustus. Tiberius. Gaius Caligula. Translated by J. C. Rolfe. Introduction by K. R. Bradley. Loeb Classical Library 31. Cambridge, MA: Harvard University Press, 1914.

Taelman, D. (2014). Contribution to the use of marble in central Lusitania in Roman times: The stone architectural decoration of Ammaia (São Salvador de Aramenha, Portugal). Madrid, 87, p. 175-194.

Taelman, D., Elburg, M., Smet, I., Paepe, P., Lopes, L., Vanhaecke, F., Vermeulen, F. (2013). Roman marble from Lusitania: petrographic and geochemical characterization. Journal of Archaeological Science, 40, 2227-2236. DOI: 10.1016/j.jas.2012.12.030.

Taylor, R. (2020). "El "pagus marmorarius" de Almadén de la Plata: revisión de las evidencias arqueológicas y aproximación a los patrones de poblamiento romano en el distrito marmóreo". Monografías de Prehistoria y Arqueología UNED,1, p. 89-116.

Trapero Fernández, P., Carneiro, A. & Moreira, N. (2023). Transport and distribution of heavy loads in ancient times: Estremoz Marbles in the Roman province of Lusitania. Journal of Archaeological Science: Reports, 49, 103962. DOI: 10.1016/j.jasrep.2023.103962.

Vidal Álvarez, S., García-Entero, V. & García-Moreno, A. G. (2017). La utilización del mármol de Estremoz en la escultura hispánica de la antigüedad tardía: los sarcófagos. digitAR, 3, 119-128. DOI: 10.14195/2182-844X_3_14.

Wielgosz-Rondolino, D. W., Antonelli, F., Bojanowski, M. J., Gładki, M., Goncüoglu, M. C. & Lazzarini, L. (2020). Improved methodology for identification of Goktepe white marble and the understanding of its use: A comparison with Carrara marble. Journal of Archaeological Science, 113, 105059. DOI: 10.1016/j.jas.2019.105059.

Zöldföldi, J. (2011). 5000 Years Marble History in Troia and the Troad. Petroarchaeological Study on the Provenance of White Marbles in West Anatolia. PhD Thesis (unpublished), University of Tübingen, 290p.