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Geodiversity assessment through the Évora – Montemor-o-Novo region: On the scope of valorising the mining heritage of the Ossa-Morena Zone (SW Iberia, Portugal)

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Abstract

The SW of Iberia registers diverse examples of mining remnants from activities that ceased during the 20th century, namely in the Ossa-Morena Zone. Such activities exposed outcrops that make part of the mining heritage of the Alentejo province (Portugal), and examples of that are found throughout the Évora – Montemor-o-Novo region at the ancient Montemor-o-Novo iron mines. The area, comprised within the *Évora Massif*, besides displaying an important mining and quarrying heritage, also exhibits important geomorphological, structural, and lithological features that are key to understand the geodynamic evolution of the Variscan Orogeny at the SW of Iberia.

This work intends to evaluate the geodiversity throughout the region and propose routes that integrate geodiversity features along with the mining heritage of the ancient mines from the Montemor-o-Novo iron district. Furthermore, the region is characterised by immense cultural, historical and archaeological assets that together with the geodiversity of the region have efficiently been used for scientific and formal and informal educational purposes.

Mining heritage can contribute to the understanding of the role of mineral resources on the past, present, and future of society as we know it. The proposal herein disclosed although intending to promote geoconservation strategies regarding the mineral resources of Ossa-Morena Zone does not aim to make exploration and mining unfeasible in these locations. On the contrary, this work intends to promote strategies in which industry and geoheritage can work together on the knowledge transfer to society, contributing to the geological literacy.

1. Introduction

Society, as we know it, emerged and has been shaped by the necessity of life quality enhancement, and with it the indissociable increasing need for mineral resources. To achieve such goals the pursuit for raw materials, many of which provided by mineral deposits, has promoted human migrations and territorial occupation throughout history, such as the well-known Punic and Roman occupancy of the Iberian Peninsula which is an uttermost example of mineral resources exploration and mining. Diverse examples of Roman occupation are found in the Iberian territory, mainly in what concerned gold and tin exploration. Remnants of the Roman mining activities can be found throughout Iberia, with some of those sites having been studied for their geological, educational, and scientific value, such as the Tresminas, Valongo and Castromil Roman gold mines in NW Portugal (e.g. Lima et al 2010; Fonte et al 2017; Cruz et al 2018), and the Las Médulas Roman Gold Mines in NW Spain (e.g. Matías and Llamas 2021). This intricate relation between mineral resources, historical, cultural and archaeological heritage should be considered in a geodiversity assessment and geoconservation strategy, since they could be used to widen the audience range to these geodiversity sites. The Évora – Montemor-o-Novo region is one of the regions that can benefit from such a strategy as it comprises a complex geological evolution which is key to reconstructthe geodynamic evolution of Iberia through the Cadomian and Variscan orogenies. The geological complexity is allied with the fact that human settlements in the area go back as far as the

Palaeolithic, and due to the metallogenic characteristics of the region it has also been the target of iron exploitation during Roman times. The iron mining history continues up to the 20th century, marking an important era of industrial development. Furthermore, the potential for future exploration still exists, particularly at the *Escoural* area, which has been the target for several research and exploration projects focusing on gold mineralisation (Ribeiro et al 1993; Inverno 2001; Maia et al *submm.*).

Throughout this work the assessment of 10 locations with the potential for geodiversity and geosite classification is provided. We intended to propose a geodiversity route between Évora and Montemor-o-Novo municipalities that focuses on the relevant mining heritage of the Montemor-o-Novo ancient iron mines area.

These mining areas are located in the vicinity of the Santiago do Escoural Village, at approximately 13 km west of the Évora municipality, classified by UNESCO as a World Heritage City since 1986.

Some of the locations described throughout this work have already been considered for previous geoconservation strategies, and two of them are already catalogued as geosites, such as the *Herdade Monte das Flores* quarry (Brilha et al 2008, 2010) and the *Escoural* caves (Brilha et al 2008, 2010; Brilha and Pereira 2020). Unfortunately, the potential of the region is still not fully taken advantage of, lacking the existence of a common framework for geodiversity between both municipalities.

The work here presented is motivated by the necessity of increasing the awareness about mineral resources usage and their applications to every-day life, and their importance in achieving the 2030 Sustainable Development Goals proposed by the United Nations Organization, as well as in developing a consistent strategy for the beneficiation of geodiversity of mining heritage in the geotectonic Ossa-Morena Zone, with an integrative approach that considers other geological, cultural and historical heritage sites. Through the last decades efforts have led to the definition of the Geosite Frameworks of Portugal (Brilha et al 2005, 2008, 2010). Unfortunately, the mining areas of Ossa-Morena Zone were not considered, with exception to framework xxviii) Gold Mineralizations (Brilha et al., 2008), applicable to all Portuguese territory. Nevertheless, several crucial frameworks for Geoconservation in Ossa-Morena Zone have been defined, such as the framework iv) Silurian of the Portuguese Ossa-Morena Zone and xxiv) Pre-Mesozoic granitoids (Brilha et al., 2008).

Despite mining heritage usually being left out of the Geological Heritage and Geosite definition umbrella (Brilha et al 2016), several authors argue in favour of its consideration (López-García et al 2011; Prosser et al 2018; Mazadiego et al 2019; Giocada et al 2019), as it should be considered an important part of those definitions as mining heritage provides sites with proven scientific and educational values (Hellqvist 2019), and such is the case of the Montemor-o-Novo ancient iron mines.

2. The Geology Of The Ossa-morena Zone

The SW border of the Iberian Massif is the outermost terrane of the European Variscides, which separates the tectonostratigraphic terranes of Ossa-Morena Zone (OMZ) and South Portuguese Zone (SPZ). The geodynamic evolution of OMZ is conditioned by the Rheic Ocean opening and closure, part of the Variscan Cycle (Ribeiro et al. 2007; 2010) and which can be simplistically framed in the light of the Wilson cycle (Wilson et al. 2019) as follows: Stage 1) early stages of continental rifting at northern Gondwana (Middle Cambrian) mark the beginning of the Variscides evolution that will significantly overprint structures from a previous orogeny (Cadomian Orogeny); Stage 2) Rheic Ocean opening (500 – 470 Ma.) marking the detachment of Avalonia from Gondwana; Stage 3) The achievement of a mature passive margin when Rheic becomes a wide ocean (Ribeiro et al. 2007); Stage 4/5) Beginning of the compressional regime and oceanic crust subduction under the Gondwana terrain (425 – 410 Ma.); Stage 5) As compression continues the Avalonia – Gondwana approximation culminates in an oblique collision (390 – 370 Ma.) that marks the beginning of the continental orogen, the suture of this collision is preserved by the contact between OMZ and SPZ; Stage 6) The final stages of the Variscan Orogeny are achieved by dextral transpression between Avalonia and Gondwana (aprox. 290 Ma.;Ribeiro et al. 2007).

The OMZ is limited at NE by the *Tomar-Badajóz-Córdoba shear zone*, which is interpreted as a Cadomian suture between the OMZ terrains and Central Iberian Zone (CIZ) latter reactivated during the Variscan Orogeny as a transpressive shear-zone (Ribeiro et al 2010; Araújo et al 2013). The SW limit, between OMZ and SPZ, is materialised by the *Beja-Acebuches Ophiolitic Complex*, which corresponds to an obducted oceanic crustal fragment during Rheic closure (Ribeiro et al 2010), and by the *Beja Igneous Complex* which marks the emplacement of mafic to intermediate magmatic bodies (Jesus et al 2020).

The basement of OMZ is characterised by a thick Neoproterozoic metasedimentary sequence that results from the dismantlement of a Cadomian magmatic arc, referred as *Série Negra* in Iberia.

The Rheic closure marks the beginning of intense tectonism with metamorphic conditions being ubiquitously kept at the greenschist and amphibolitic facies. The compressional regime led to the oblique collision between Avalonia and Gondwana (390 Ma – 390 Ma; Ribeiro et al 2007) triggering the thrusting of autochthonous and allochthonous terrains over the metasedimentary basement in the inner domains of Iberia (Araújo 1995; Ribeiro et al 2010). Such events are promoted by the transcurrent collision between Avalonia and Gondwana, which also marks the beginning of several tectono-metamorphic and magmatic events, such as those that form the *Évora Massif*.

2.1. The *Évora Massif*

The complexity and geological heterogeneity of the region are expressed by the wide and extensive *Évora Massif* terrains, situaded between Évora and Montemor-o-Novo municipalities. The *Évora Massif* is located at the NW of the *Montemor-Ficalho belt* (Oliveira et al 1991, Araújo 1995), which correspond to the *Évora-Beja-Aracena* domains (Chacón et al 1983; Apalagueti et al 1990) and marks the suture of a continental collision (Ribeiro et al 2007, 2010). The *Évora Massif* was internally subdivided into three main metamorphic domains: i) the *Montemor-o-Novo Shear Zone* (MNSZ), ii) the *high-grade metamorphic terrains*, and iii) the *Évora mid-grade metamorphic terrains* (Pereira et al 2003, 2006, 2007; Chichorro 2006; Moita et al 2009; Moita 2007; Dias da Silva et al 2018). The *Évora Massif*, particularly the high-grade metamorphic terrains, are evidence of the complex geodynamic context of the SW of OMZ, with reflections of the transcurrent continental collisional stages controlling the intense WNW-ESE deformation and the calc-alkaline magmatic activity throughout the suture zone. This magmatic activity is interpreted as being triggered by oceanic plate subduction during the Rheic Ocean closure and subsequent slab break-off mechanisms, leading to the emplacement of several calc-alkaline plutons during Early-Carboniferous (e.g. *Beja Igneous Complex*; Jesus et al 2016, 2020). Throughout the *Évora Massif* evidence for such activity is materialised at the high-grade metamorphic terrains, where the Hospitais tonalite and the *Alto the São Bento* granitic suites have been emplaced.

i. The *Montemor-o-Novo Shear Zone* (MNSZ) is part of the hanging-wall of the *Évora Massif*, and corresponds to a NW-SE deformation corridor, developed during the late-collisional stages of the Variscan orogeny, in which the metamorphic conditions were sustained in the greenschist to amphibolic facies. MNSZ displays a lithostratigraphy highly controlled by the left-lateral movement and affects three main units, as follows: 1) A Neoproterozoic metasedimentary sequence, locally referred as *Escoural Formation* (560-550 Ma; Chichorro 2006), mainly composed of mica-schists, paragneiss and local amphibolite intercalations. 2) A carbonate unit of Cambrian ages (*Monfurado Formation*), ubiquitous throughout the Ossa-Morena Zone, which was locally divided into two main units (Chichorro 2006): a lower unit displaying abundant acid metavolcanic rocks with rhyolite-rhyodacite affinities (522 ± 5 Ma; Chichorro 2006; Chichorro et al 2008) emplaced within the carbonate units and interpreted to mark intense rift-related volcanic events (Sánchez-Garcia et al 2003, 2019; Chichorro 2006); and a upper unit corresponding to a gradual transition to less altered and coarse-grained marbles, and marking the transition to basic volcanism, locally evidenced by the amphibolites interbedding. 3) At the top of the *Monfurado Formation*, the ubiquitous presence of amphibolites and metabasites, locally called *Carvalhal Formation* (Carvalhosa 1983; Carvalhosa and Zbyszweski 1994), suggest that during the Upper Cambrian – Ordovician? the basic volcanic events intensified, latter metamorphosed into the greenschist and amphibolitic facies.
ii. The high-grade metamorphic terrains of the (**Fig. 1b**) correspond to a 15-20km belt composed by the *Gneiss-Migmatite Complex* (GMC; Carvalhosa and Zbyszewski 1994) and intruded by several magmatic complexes (tonalites and granites) targeted for several geochemical and geochronological studies (Chichorro 2006; Moita 2007; Moita et al 2009, 2015; Pereira et al 2007, 2015; Dias da Silva et al 2018). These studies focused on the genesis of some of the intrusive magmatic bodies (*Hospitais Tonalite Massif* and *Alto de São Bento Granitic Suite*), as well as in identifying the complex conditions in which migmatization occurred at the *Gneiss-Migmatite Complex* (e.g. Migmatites at the Almansor River).

This complex corresponds to a diatexitic-anatetic migmatite complex which, at the contact with the *Hospitais Tonalite Massif*, displays an extremely heterogeneous structure with individualisation of several migmatization textures such as diatexites and metatexites and amphibole-rich restites with geochemical signatures that suggest crustal anatexy of the Neoproterozoic metasediments. The ages for

GMC were constrained around 341 Ma (Pereira et al 2015), indicating that migmatization events should slightly precede the elongated WNW-ESE *Hospitais TonaliteMassif* installation with 337-336 Ma. and characterised by ubiquitous medium to coarse-grained tonalite, which displays sparse mafic enclaves with diorite affinity (Moita, 2007; Moita et al 2015).

The *Alto de São Bento Granitic Suite* is a suite of plutonic rocks characterised by two-mica leucogranite and porphyritic granites with mafic enclaves, similar to the ones described for the *Hospitais Tonalite Massif* (Moita et al 2015) and with ages around 336.7 Ma ± 3.2 Ma (Pereira et al 2015). The leucogranites are strongly peraluminous with calc-alkaline signatures coherent with the geodynamic settings that triggered magmatism in the SW of OMZ. The porphyritic granites are characterised by large crystals of alkali-feldspar, with sparse large mafic enclaves and by several pegmatitic-veins (Moita et al 2009).

iii. The Évora mid-grade metamorphic terrains is part of the hanging-wall at the NE of the *Évora massif* (Pereira et al., 2015; Dias da Silva et al., 2018) and corresponds to a wide sector affected by amphibolitic facies metamorphism and composed of metasedimentary rocks (schists, amphibolites) and gneisses, intruded by the *Divor* and the *Pavia* Carboniferous plutons (Dias da Silva et al., 2018).

The research here presented focus on the *Montemor-o-Novo Shear Zone* terrains, which comprise a complex metallogenic setting responsible for the formation of several iron and gold deposits, some of which part of the Montemor-o-Novo iron mining district.

3. The Montemor-o-novo Iron Mining District

The ancient mines from the Montemor-o-Novo iron district (**Fig. 1**) are located at the SW of the Ossa-Morena Zone, close to the Montemor-o-Novo municipality, which gives the name to the mining complex, and to the Santiago do Escoural village, in the Monfurado Mountain range (441 meters). Evidence for human occupation in the area dates back to the Palaeolithic age based on wall paintings and artefacts (100 000 bC – 10 000 bC; Silva et al 2017), and therefore, the use of mineral resources (including for the pigments used on the wall paintings) for human well-being is assumed to have occurred in the area from those times up to the Roman occupation of Iberia, later succeeded by modern mining in the 20th century.

Such a long mining history has produced not only landscape transformations (e.g., the presence of mine tailings and open pits), but also the cultural and historical heritage of the region. Examples of this are recognised in the toponymy of the Monfurado Mountain and the Santiago do Escoural village. The name of the mountain range (*Monfurado*) derives from the agglomeration of *Monte* (=range/small mountain) *Furado* (=bored/excavated/with cavities), owing its name to the ubiquitous excavations seen throughout the mountain which are attributed to Roman mining works. Another explanation for this name could be related to the karst morphologies associated with the limestones and marbles of the Monfurado range, such as the ones observed at the Escoural Caves (see section 4.). The Monfurado range corresponds to an area protected under the “Natura 2000” network, considered as a Special Conservation Zone aiming to protect and preserve important natural habitats.

The Santiago do *Escoural* village name is considered to have its origin related to the iron exploration and beneficiation during Roman times. The *Escoural* name could have derived from *Escorial*, which means “a field of slag”, due to the findings of several tailings of slag through the area considered to have been produced during Roman iron mining works.

Long after the Roman occupation the Montemor-o-Novo area was the target for iron exploitation through ten concessions along a 10 km NW-SE belt (**Fig. 1c**), in which open-pit and to a lesser extent underground mining was carried out from 1865 until 1929 (Andrade et al 1949).

3.1 Ore deposit geology

The geodynamic evolution of the SW Iberian Variscides sustained conditions suitable for the formation of ore deposits associated with rift-related submarine volcanism during the opening of the Rheic Ocean

Example of such metallogenic systems is the Montemor-o-Novo iron deposits (Salgueiro 2011; Salgueiro et al 2012; Mateus et al 2013), to which a classification as SEDEX and VMS deposits were attributed due to their geological settings at the presumable time of formation and ore assemblage, mainly constituted by massive magnetite bodies and massive sulfide layers (Maia et al *in press.*). Sedimentary exhalative (SEDEX) deposits are formed near seafloor submarine hydrothermal vents that promote the precipitation of metals (Cu, Pb, Zn) in stratiform bodies, usually hosted by shales and siltstones. The conditions that lead to SEDEX deposits formation are intrinsically related to rift-related events, in which rifting promotes the formation of hydrothermal vents that leach metals from the surrounding host rocks (Hannington 2021; Wilkinson 2014).

The Volcanogenic massive sulfide (VMS) term refers to deposits formed in a submarine environment near large episodes of submarine volcanisms many times triggered during the rifting stages of an orogen. The VMS deposits are usually rich in base metals (Cu, Zn, Pb), and found in massive sulfide lenses composed of more than 60% of sulfides (Hannington 2014), mostly pyrite and pyrrhotite.

The iron ores from the Montemor-o-Novo deposits are mainly hosted as massive lenticules in the Monfurado Formation marbles, although disseminated and massive magnetite is also found at depth (intersected by drill cores; Maia et al., *in press.*). The host carbonate units display intense amphibole development close to the ore horizons, which is in some cases the reflection of the metamorphism in the greenschist to amphibolitic facies. The relation of the iron ores and the host rocks has led to the interpretation that consider them as being syngenetic and therefore magnetite formation should be contemporaneous of the Cambrian sedimentary carbonate formation.

The continental orogen stage of the Variscan Orogeny (390 Ma – 370 Ma: Ribeiro et al., 2007) promoted the formation of several deposits related to such geodynamic context, such as the Escoural Orogenic gold deposits (Ribeiro et al 1993; Inverno 2001; Maia et al., *in press.*) found near the study area. These deposits mainly occur in the vicinity of the *Boa-Fé* fault, within the MNSZ, and are hosted in quartz veins crosscutting the Escoural Formation metasedimentary succession, in which gold-arsenopyrite-loellingitemaldonite assemblages have been identified. Gold mineralisation is structurally controlled by the Variscan MNSZ activity (356 – 322 Ma; Pereira et al 2012, 2015), with vein development mainly associated with a brittle-ductile transition. The spatial relation between the iron ores and gold mineralisation has been discussed in recent works (Maia et al., *in press.*).

4. Geodiversity Assessment

The insufficient geological literacy, particularly in Portugal, is in part due to the inappropriate and unproportionally teaching of geology through middle and high school, when compared to other natural sciences (Reis et al 2014). This inefficiency leads to a deficient awareness to the role of mineral resources in society. This becomes a problem when it is necessary to grasp environmentally responsible exploration and mining projects, leading to problems with local communities and therefore in acquiring the necessary social license to operate. Geologists have their share in this problem, since normally it is quite difficult to deconstruct some of the concepts of geology (*sensu lato*), and particularly the ones related to exploration and mining, to a non-specialised public. For this, the assessment of geodiversity and mining heritage by cataloguing and promoting the scientific and educational value of key locations is of major importance.

The Évora – Montemor-o-Novo districts comprise attractive and didactic geosites and geodiversity sites that display a strong relationship with several cultural and historical values of the region that could, and should, be used in informal and formal teaching activities focusing on the local and regional geology. A total of ten sites, both outside and inside the ancient iron mining area (**Fig. 2**), are outlined as being able to integrate a geological and cultural route between Évora and Montemor-o-Novo (**Fig. 2**). Limelight will be focussed on the mining heritage located in the Montemor-o-Novo municipality, near the Santiago do Escoural village, since geodiversity characterisation and assessment within these areas raises more concerns in terms of geoconservation due to the rapid deterioration of some of the mining heritage sites.

The description of geodiversity is herein addressed both for the outside and inside of the ancient Montemor-o-Novo mining district, aiming to propose a geodiversity route that interlinks the Évora and Montemor-o-Novo municipalities. A qualitative assessment (Brilha et al 2016, 2018) of individual potential location is provided through the next sections, as well as a tentative quantitative assessment of Geodiversity regarding the Scientific (SV), Educational (EV) and Touristic values (TV) of the locations proposed to integrate the geodiversity route, allied with the degradation risk assessment following the criteria defined by Brilha et al (2016). The quantitative assessment results can be consulted in **Supplementary Material A**. A score from 1 to 4, is attributed to each site selected to integrate the geodiversity route, with exception of the *Almendres Dolmen Complex* since it does not meet the criteria to be considered a geodiversity location Nevertheless, the *Almendres Dolmen Complex* was most probably constructed using local granitic stones, and due to its significant archaeological and cultural heritage is herein considered as an important asset for the route. The numbering of the sites is shown in accordance to **Figure 2** and does not represent the sequence of visitation for the potential geodiversity route (see section 6.). The list of the sites both inside and outside of the ancient mining area can be found in **Table 1**.

4.1. Geodiversity and geosites outside the ancient mining area

Alto de São Bento granitic suite (Ancient Quarry)

The *Alto de São Bento* area is a geomorphological feature of the Évora landscape, located at around 3 km from the city centre, and corresponds to an elevation (aprox. 360 m) that contrast with the surrounding characteristic Alentejo plains. At the area, outcrops of two-mica leucogranite and porphyritic granites (**Fig. 3a**) were exposed by quarrying activities during the 20th century and are now accessible to the public. The contrasting altitude of Alto de São Bento with the surrounding landscape was an important factor for the settlement of several windmills used for seed processing.

The geological, biological and cultural assets of the area are currently musealized (Brilha & Carvalho 2010) by the Évora municipality, which developed a museum that offers several educational and touristic activities, allied with the fact that the *Alto de São Bento* area offers one of the most beautiful sight-seeing sceneries over the Évora UNESCO city (**Fig. 3b**).

Several geological features are displayed at the outcrop, such as the ubiquitous course-grained porphyritic granite with abundant K-feldspar phenocrysts which display concentric zoning (**Fig. 3a**) and a medium grained two-mica leucogranite. The porphyritic granite facies also exhibit large mafic enclaves of igneous material (biotite-rich; **Fig. 3a**) that put in evidence fractional crystallisation processes (Moita et al 2009).

Considering the described characteristics, it is evident that the substantive scientific, educational and even touristic values of the area, with scores of 3.1, 3.3 and 2.9 respectively, flag it as a potential geosites location, benefiting from the musealization and conservation already developed in the area. Furthermore, the Alto de São Bento granitic suite could easily be integrated in the Pre-Mesozoic Granitoids framework of the Portuguese Geosite Inventory (PGI; Brilha et al 2005, 2008, 2010), and for this reason this site is herein considered a mandatory geodiversity stop in the geodiversity route proposed through section 6.

Herdade Monte das Flores Quarry

The *Monte das Flores Quarry* is an example of geodiversity in the Évora Municipality, located at circa 6 km from the city centre, it is part of the PGI framed on the Pre-Mesozoic Granitoids (Brilha et al 2008, 2010) and publicised on the ProGEO – Portugal website. The quarry is located at the Évora Massif, and extraction is devoted to the Évora granite/ granodiorite facies for industrial uses (Industrial rocks). The quarry was classified as a geosite due to its geological, economic, cultural, archaeological, and educative value. The most relevant features are associated to the use of the Évora granites as building-stones from the Megalithic period until the present days. Evidence of that is the *Almendres Dolmen Complex* (see next section).

Almendres Dolmen Complex

The *Almendres Dolmen Complex* corresponds to a cromlech archeologic structure located at circa 7 km of the UNESCO Évora city and is composed of 95 Neolithic granitic monoliths (**Fig. 3c**), arranged in a circle. The site was classified as a National Monument in 2015, and besides being an example of archaeological heritage, the geological aspects of the monument, like the nature of the rock utilized in the construction, can also be used for educational purposes.

Although the *Almendres Dolmen Complex* does not fit the criteria for geological heritage, if inserted in the geodiversity route, this site could be used as an example of the societal and cultural evolution associated with the use of geological resources. This monument is part of the Megalithic Route, promoted by the Évora Municipality, and although tourists intensely visit the area, it lacks proper interpretative communication, better road access, infrastructures, and visitation circuits.

Migmatites at the Almansor river

The Almansor area corresponds to an outcrop that displays the perfect conditions for the observation of the high-grade metamorphic terrains from the Variscan *Gneiss-Migmatite Complex*, part of the *Évora Massif*.

The area is located along the left and right margins of the Almansor river that contours the Montemor-o-Novo municipality (ca. 2 km from the city centre). At the outcrop scale several petrogenetic features have been individualised by several authors, such as diatexites, weakly foliated granitoids and trondhjemitic veins (Moita et al 2009). The high-grade metamorphic terrains register the effects of intense migmatization of the metasedimentary country rocks (Escoural Formation), in which partial fusion (crustal anatexy) is evidenced by the presence of diatexites, metatexites, restites and numerous mafic enclaves observed through the area, revealing variable fusion rates.

The diatexites-metatexites mark the migmatization flow (**Fig. 3d**) commonly exhibiting centimetric to metric restites of metamorphic origin (Moita 2007; Moita et al 2009), possibly reflecting metasedimentary host rock blocks, from the Escoural formation, that did not undergo total fusion and in which pre-migmatization textures are sometimes preserved (**Fig. 3e**).

The diatexites and metatexites are composed of leucosome and melanosome components (**Fig. 3e**) and the relation between the GMC and the adjacent *Hospitais Tonalite Massif* is evidenced by the weakly-foliated granitoids present in the area (Moita et al 2009).

As gathered from the previous description, and reinforced by the SV, EV and TV scores (**Supplementary Material A**) of 3.6, 3.1, and 2.65, respectively, it is here suggested that the area has the potential to be classified as a geosite framed in the Pre-Mezosoic Framework of the PGI Inventory (Brilha et al 2008 2010). Furthermore, there has been a previous proposition for the creation of two Eco-trails through the Almansor river margins (Dias da Silva et al 2006), which contemplates the geological, cultural and landscape characteristics of the area. The geoconservation strategies that could possibly be implemented should focus on the implementation of interpretative centres focusing on the representative and rare geological processes displayed through the outcrops. Besides the proposals from other authors, we believe that contemplating this site in a geodiversity route is extremely important in interpreting regional geological settings.

4.2. Geodiversity and geosites inside the ancient mining area

Nogueirinha and Serrinha mine

The *Nogueirinha* and *Serrinha* mines were two of the main open-pit exploitation areas corresponding to two of the 10 mining concessions part of the ancient Montemor-o-Novo iron district (**Fig. 1**). Both mines are located approximately at 26 km and 21 km from Évora and Montemor-o-Novo municipalities, respectively. Mining activities were sustained from 1876 until 1929, and the total amount of exploited iron ores are estimated at around 137 406 tons (Andrade et al 1949), which at the face of current societal supply and demand is considered insignificant.

Currently, the open-pit mining areas are abandoned and have not been the target of any geoconservation proposals. They are both located inside private owned lands, although access is usually granted for educational and scientific purposes. From a visitation point of view these proposed locations are the ones that raise more concerns regarding security and accessibility to the outcrops, but nevertheless field work is possible.

Remnants of the ancient mining works are ubiquitously denounced by large volumes of tailings in both *Nogueirinha* and *Serrinha* mines. At the *Serrinha* mining area, the access to the outcrop is easier, and primary magnetite ± primary pyrite mineralisation can be observed.

The quantitative assessment of both locations revealed SV; EV and TV of 1.75/1.9, 2.2/2.2 and 2.2/2.2 respectively.

Escoural cave

The *Escoural caves* is a geosite framed in the "*Karst Systems of Portugal*" classified by the PGI (Brilha et al 2008, 2010; Brilha and Pereira 2020) and corresponds to a typical carbonate karst system, located at approximately 15 km from the Montemor-o-Novo municipality (**Fig. 2**). The cave was accidentally discovered in 1963 during quarrying works in the area, which focused operations on marble extraction for ornamental purposes. The marbles belong to the Cambrian Monfurado Formation (Chichorro 2006). Allied with the karst other geological features are identified, such as stalactites and stalagmites (**Fig. 3f**).

Besides the described geological features, that classify the *Escoural cave* as a geosite, carvings and paintings found on the cave walls demonstrate that the karst system was used as a shelter for human settlements since the Palaeolithic (Silva et al 2017). The discovery of these findings has classified the cave as a national monument due to its major archaeological value.

Hence, the *Escoural cave* has been the aim of several conservation interventions and academic research in a wide range of scientific fields (e.g. Caldeira et al 2021). Visitation is currently possible, although prior booking with the Montemor-o-Novo municipality is mandatory. The guided tour through the small cave takes approximately 30 minutes and can be organised in groups of up to 10 persons (pre-COVID). Although the cave displays interesting geodiversity features, the visitation currently only focuses on the pre-historic archaeological features of the monument. The geodiversity quantitative assessment of the *Escoural cave* revealed SV, EV and TV scores of 3.1, 3.3 and 3.25 respectively, supporting the geological significance of the monument. We believe that since the area is already classified as a geosite, the guided tour in the *Escoural cave* should also focus on the geological features of the karst system, and if so, should integrate the herein suggested geodiversity route.

Serra do Conde Quarry

The *Serra do Conde* area corresponds to a differential erosion relief (439 m) part of the Monfurado Mountain range, located at approximately 23 km from Évora and 21 km from the Montemor-o-Novo municipalities.

At the *Serra do Conde* area outcrops of amphibolites from the *Carvalhal Formation* (**Fig. 1; Fig. 4a**) occurring in the core of a synclinal structure can be observed (**Fig. 4c;** Chichorro 2006). The amphibolites display a nematoblastic texture and two main metamorphic-deformation fabrics can be seen. One parallel to an S_0 foliation with a N325º direction and sub-vertical dipping, strongly marked by the development of epidote (**Fig. 4b**). Primary foliation is transposed by a generally folded S_1 mylonitization (N145º direction; **Fig. 4b**). The rock quality and weak fracturing fomented the extraction of several blocks as ornamental stone, and therefore the outcrops at the Serra do Conde area were exposed by the quarrying activity.

The area contributed to scientific research that focused on the interpretation of the regional and structural geological settings (Chichorro 2006) reinforcing the scientific value score of 3.2 (**Supplementary Material A**). Access to the area can be done by foot or by SUV through an earth road (approximately 1.5 km from the nearest paved road). The described characteristics of the *Serra do Conde Quarry* resulted in EV and TV scores of 1.95 and 2.05 respectively, although we believe that the educational value is far greater than the touristic value.

Vale da Arca Mine

Vale da Arca Mine is located at circa 16 km and 25 km from the Montemor-o-Novo and Évora municipality and contributed with a minor amount of ore production to the overall tonnage of the Montemor-o-Novo iron district, although concrete numbers are not known (Andrade et al 1949). The mine was abandoned during the early 20th century, although it was latter used for quarrying activities that focused on the extraction of the marbles. The quarry is presently abandoned, but both the mining and quarrying activities exposed outcrops that allow for the characterisation of geodiversity features related to the geodynamic and structural settings of the MNSZ

For the present work the Digital Elevation Model (DEM) was constructed using drone imagery collection in the Vale da Arca area (**Fig. 5**), and five geological features of the outcrops are outlined (**Fig. 5**): 1) Observation marbles with olivine and disseminated magnetite ± pyrite mineralisation. This lithotype belongs to the *Monfurado Formation* marbles and here it is possible to understand that the disseminated textures and low tonnage were probably the reasons why the mine was abandoned; 2) Boudinage structures of a silicious layer interbedded within the olivine marbles (**Fig. 6a**) resulting from the different mechanical/rheological competence between the marbles, with a ductile behaviour, and the silicious layer which has a brittle behaviour, generated due to the overall NW-SE deformation associated to the MNSZ activity. Boudinage structures such as chocolate tablet boudinage and inter-boudin (**Fig. 6c**) and necking structures (**Fig. 6d**) are observed in this site; 3) At the area, beds of massive pyrite ± magnetite layers can be observed (**Fig. 6b**) and usually exhibit surficial oxidation (**Fig. 6b**). These beds are over thrusted (N355º; 40ºE) by pristine course-grained marble lithotype, which correspond to point 4 in **Figure 5; 5**) The upper unit of the *Monfurado Formation* marks the initial stages of Cambrian basic volcanism, with abundant intercalations of metavolcanic coarse-grained rocks, which can be observed in this point. These rocks exhibit large crystals of amphibole, epidote and feldspar (**Fig. 6e**).

The pin-pointed geological features (**Fig. 2**) show the relevance of these outcrops for a possible geodiversity route, which favour the accessibility conditions of the *Vale da Arca Mine*. The SV, EV and TV scores (2.1, 2.5, 2.4; **Supplementary Material A**) reinforce the proposition of the *Vale da Arca* area as a geosite that would easily be integrated in a geodiversity route.

Ongoing research focusing on trace element composition of magnetite (Maia et al. *in prep.*) found evidence for the deposition of sphalerite (ZnS) along late stages of magnetite deposition. The textures found on magnetite crystals indicate that sphalerite is associated with the porous rims (**Fig. 6f**), where they occur as inclusions along with pyrite (**Fig. 6g – green Zn distribution**). Such findings might be good indications for future mineral exploration in the area, which should not be constrained by future geoconservation strategy because the mining potential of the area should be an ally of the use of the area for scientific, formal and informal education activities.

Monges Mining Complex

The *Monges Mining Complex* correspond to the biggest mining works part of the Montemor-o-Novo iron district. The area is located approximately 10 km from the Montemor-o-Novo and 35 km from the Évora cities. Mining works were mostly performed in open pit, although locally underground mining was adopted, with ore production estimated around 206 783 tons, which correspond to 60% of the iron production in the sector (Andrade et al 1949).

The *Monges* mine (Monges = Monks) owe its name to the existence of an Abbey (**Fig. 7a**) which construction dates to 1738 and served hermit monks that inhabited the Abbey until 1834. After the abandonment, and with the discovery of the iron ores, the Abbey was used to lodge many of the miners that worked at the mine site (Andrade et al 1949). Currently, the beautiful building is in ruins (**Fig. 7a**) due to an unfortunate lack of architectonic conservation strategies.

The remnant open-pit mining activities are currently dominated by intense vegetation which outlines nature restoration promoted by natural processes combined with human abandonment. Even though access is difficult, at the area large mine tailings can be observed, as well as *in-situ* ore bodies. As previously described, mining activities in the region are thought to date back to the Roman period, and at the time iron ores were found due to the intense leaching capping (gossan zone) that are an evidence of intense iron-oxide surficial alteration (**Fig. 7c**).

The massive ore bodies are mainly constituted by magnetite (± pyrite ± chalcopyrite) and perfect crystallisation of magnetite is ubiquitously observed (**Fig. 7b**). The effects of pyrite exposure to atmospheric conditions are observed at the outcrop scale, and the oxidation of pyrite results in sulphates and native sulphur formation, denounced by its characteristic yellow colour (**Fig. 7d**). Microscopic examination of magnetite samples collected at the *Monges* open pits (**Fig. 7e and f**) revealed euhedral magnetite crystals with porous textures and homogenous chemical compositions (**Fig. 7f**), but with sparse silicate inclusions.

The examination of the *Monges Mining Complex* indicates that this is one of the prime examples of mining heritage in the region and is herein proposed to integrate the Portuguese geosites list, although a framework that considers the mining heritage of Ossa-Morena Zone would have to be proposed. This proposition is supported by the obtained SV and EV quantitative assessments (**Suplementaty Material A**). Although some accessibility conditioning is identified, such as the access by an earth road and by foot, the area also displays the necessary conditions for a trekking route, taking advantage of the Monfurado Mountain habitats and characteristic vegetation (*Quercus Suber*).

5. Proven Educational Value

Proven educational and scientific value of the Évora – Montemor-o-Novo region is recognised by the many scientific papers (e.g. Moita et al 2009, 2015; Chichorro et al 2008; Salgueiro 2011; Pereira et al 2003; 2006, 2015; Dias da Silva et al 2018; Maia et al., *submm.*) and educational activities continuously being developed, both addressing the lithological and metallogenic diversity of the area.

Most of the educational activities carried out through the area are dedicated to geology bachelor and master's degree students, and one of the reasons why this is continuously done is the proximity to the University of Évora. During the last four years, the dynamization of several activities in the area was done by the project "ZOM3D: 3D Metallogenic Modelling of the Ossa-Morena Zone – Valorisation of the mineral resources of Alentejo" (from now on referred as ZOM3D) and by the Geoscience Department of the University of Évora.

The activities were targeted to a geoscientific audience, and examples of that were the 2018 Spring Course and the recent 2021 accredited field course devoted to the upgrading of geological concepts targeted to professors from the basic and high-school education levels. Additionally, the Montemor-o-Novo iron district were the theme for a geoscience communication and divulgation webserie, promoted by the ZOM3D project and targeted to a Portuguese non-specialised audience. The webseries are dedicated to the iron deposits of the Fe-Zn-(Pb) *Montemor-Ficalho belt*, with special dedication to the mining heritage of the Montemor-o-Novo ancient iron mines. This webserie is composed of five episodes with lengths between the 3 to 5 minutes, promoting the use of virtual teaching resources inside the classroom. The videos were scientifically revised by the researchers of the ZOM3D project and are currently allocated in the ZOM3D project YouTube channel (https://www.youtube.com/c/ZOM3D/videos), in which several other webseries dedicated to other geological concepts and mineral resources of Ossa-Morena Zone can be found.

6. Geodiversity Route Between Évora And Montemor-o-novo

The proposal of a geodiversity route between Évora and Montemor-o-Novo municipalities was conceptualised to take advantage of several sites that have already proved their geological value, some already having been classified as geological heritage (e.g. *Escoural Cave*), and aiming for the beneficiation of the Alentejo mineral resources, in particular the mining heritage of the region (Montemor-o-Novo ancient iron mines).

This geodiversity route would serve as a geological link between the two municipalities, tightening their relationship and reinforcing that geology has no administrative borders. The qualitative and quantitative assessment of geodiversity reveals a great potential for geoconservation purposes of some of the sites, particularly the Alto de São Bento granitic suite; *Serra do Conde quarry* and *Monges Mining Complex* which display the best scores for considering them key-locations of geodiversity in the Évora – Montemor-o-Novo transect and are therefore proposed to be classified as Geosites.

Besides the geological aspects of the Geodiversity Route, it also displays additional important archaeological and cultural features that enrich its intrinsic value, such as the proximity to the UNESCO World Heritage Évora City. From another perspective, the geological diversity of the route covers several fields of Earth Sciences, from mineral resources to structural geology, and geological ages, from the Neoproterozoic up to the Carboniferous. Such features offer the possibility to travel through different stages of the evolution of the Iberian Variscan belt, presenting it at the light of the Wilson Cycle, and therefore immensely favourable for educational and scientific purposes. The proximity to the University of Évora and its state-of-the-art institutes (Institute of Earth Sciences - ICT; HERCULES Laboratory) are key factors for the viability of this route, to which the scientific know-how of these institutions could provide unique inputs.

As described, some of the locations are currently used as educational and touristic attractions (e.g. *Almendres Dolmen Complex*; *Escoural cave*), and were intervened by conservation strategies (e.g. *Alto de São Bento*), but their state of conservation is debatable and their touristic and economic beneficiation seems to fall a short from their true potential. For this reason, the geodiversity promotion proposed in this work could favour both the reinforcement of investment in the already classified areas and the beginning of a regional geoconservation strategy focusing on the Montemor-o-Novo ancient iron mining area.

The proposal shown in **Figure 8** displays a possible arrangement for the Geodiversity Route, starting from the Évora city, where several remnants of Arabic and Roman occupation can be visited (e.g., Roman Temple). Two routes are proposed for the Geodiversity Route, and as previously referred these could be adapted for public who has a geological background and for those who do not. The proposal suggests the following visitation route: 1 – *Alto de São Bento* granitic suite (**Fig. 3a and b**); 2 – Herdade Monte das Flores Quarry (Geosite); 3 – *Almendres Dolmen Complex* (**Fig. 3c**); 4 – *Nogueirinha Mine*; 5 – *Serrinha Mine*; 6 – *Escoural cave*s (Geosite; **Fig. 3f**); 7 – *Serra do Conde quarry* (**Fig. 4**); 8 – *Vale da Arca Mine* (**Fig. 6**); 9 – *Monges Mining Complex* (**Fig. 7**); 10 – *Migmatites at the Almansor river* (**Fig. 3d and e**).

Nevertheless, some of the proposed locations have aspects that could be detractors of a possible beneficiation for touristic and even educational uses of this route, such as: the difficulty to access some of the locations (e.g. *Nogueirinha* and *Serrinha* mines; *Serra do Conde* quarry); private property location (e.g. *Herdade Monte das Flores* quarry) and safety issues related to ancient mining areas. Such questions could be addressed with protocols between the municipalities and landowners for the use of private access roads to the geodiversity sites, as well as the common geoconservation strategy of the sites.

7. Conclusions

There are still many efforts to be done in what concerns the beneficiation and geoconservation of mining and quarrying heritage in Alentejo, particularly in the Ossa-Morena Zone, aiming for the use of such geosites in proper geoscience communication and awareness of the importance of mining on the economic and social development of society.

In many of the mining areas of the Ossa-Morena Zone, such as the Montemor-o-Novo ancient iron mines (**Fig. 1**), beneficiation could provide assets for local communities by the means of geotourism, with the proposition of geotouristic routes that could combine geodiversity, mining history, history, and other cultural assets (e.g., archaeological).

Many of the geodiversity sites and mining heritage, besides their geological value, display landscape sceneries that complement their significance and can attract more public to the sites, increasing the possibility of geoscience communication being effectively delivered.

As previously stated, mining is usually perceived by the public as only being connected to negative key-factors, such as, acid mine drainage, landscape degradations, and therefore tends to be demonised. Such negative opinion is undeniably related to ancient mining, in which exploitation was performed under lax environmental regulation and with insufficient or absent oversight. Even though current regulations are strict, at least for Portuguese sites, the public perception is stained by the poor examples. This brings us to one of the major problems that present exploration and mining projects face, the social license to operate, and such can only be achieved through effective and attractive geoscience communication strategies, transparency of the exploration and mining projects, and by involving the local communities in the projects. Geodiversity assessment can be a powerful ally in the awareness for the necessity and importance of mining for the society. On the reverse, mining and quarrying works can be powerful allies of geodiversity and geoconservation, as they expose geological features that would otherwise be inaccessible (Prosser 2018).

We believe that the geodiversity assessment herein presented for the Geodiversity Route between the Évora and Montemor-o-Novo municipalities should not be used as an argument to detain future exploration, mining, and quarrying projects, on the other hand we propose that in the future such projects could provide fruitful cooperation for the catalogue of important geological features, and by fomenting scientific and educational activities and further promoting the bridges between academia-industry-society. In sum, the existence of a territorial geoconservation strategy interplayed with responsible mining of mineral resources does and cannot mean the unfeasibility of future exploration, mining, and quarrying projects.

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Conflicts of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Tables

Table 1. Identification of the sites selected to integrate the geodiversity assessment with identification of owner, legal protection, accessibility, key features, and framework.

Site Name	GPS	Owner	Legal Protection	Accessibility	Key features	Framework (if applicable)*
Alto de São Bento granitic suite	38.580910; -7.937558	Public	-	Paved road (easy)	Évora Massif granitic facies	Pre-Mesozoic Granitoids
Herdade Monte das Flores quarry	38.524725; -7.954017	Private	Geosite	Paved road (easy)	Évora Massif granitic facies	Pre-Mesozoic Granitoids
Almendres Dolmen Complex	38.557508; -8.061331	Public	National Monument	Dirt road (easy)	95 monoliths from the Neolithic period, made using the local Évora granites	-
Migmatites at the Almansor river	38.645783; -8.229458	Public	-	Paved road – by foot (medium)	Impressive outcrop of the Évora Massif Gneiss-Migmatite Complex	Pre-Mesozoic Granitoids
Nogueirinha mine	38.530739; -8.124066	Private	-	By foot (hard)	Mining heritage; Mine tailings	-
Serrinha mine	38.538831; -8.136711	Private	-	By foot (hard)	Mining heritage; Ore bodies outcrops; Mine tailings	-
Escoural caves	38.543636; -8.1377728	Public	Geosite - National Monument	Paved road (easy)	Karst cave with evidence of Palaeolithic occupation	Karst Systems of Portugal
Serra do Conde quarry	38.555941; -8.131335	Private	-	By foot (medium)	Impressive amphibolite outcrops	-
Vale da Arca mine and quarry	38.548015; -8.146171	Private	-	Paved road (easy)	Monfurado Formation outcropts	-
Monges mining complex	38.573301; -8.193995	Private	-	By foot (medium)	Mining heritage; Ore bodies outcrops	-

*following Brilha et al., 2005; 2008

Figures

Figure 1

(a) Contextualization of the study area within the Ossa-Morena Zone and the Iberian Massif. (b) Simplified geological map of the Évora Massif terrains (adapted after Pereira et al 2003, 2015; Moita et al 2009). (c) Geological map of the Santiago do Escoural area and Montemor-o-Novo iron mines (Andrade et al 1949), with delimitation of the mining areas (grey dashed rectangles). The map results from the reinterpretation and adaptation from seven Geological-Mining Maps at the scale 1: 5000 (nº0/-126; nº0/-124; nº-2/-122; nº-2/-124; nº-4/-122; nº-6/-120; nº-6/-122 - Serviço de Fomento Mineiro 1960) and from previous geological mapping works (Silva et al., 1988; Chichorro 2006).

Figure 2

Digital Elevation Model projection using QGIS (plugin QGIS2ThreeJS) with the overlap of the Geological map of the Santiago do Escoural area (shown in Figure 1). Location of the Évora and Montemor-o-Novo municipalities is provided, as well as the selected locations for the presented geodiversity assessment.

Figure 3

Main geodiversity and landscape features from the Geodiversity and Geosites excluding the mining heritage and located around the Évora and Montemor-o-Novo municipalities. (a) Representative photography of the Porphyritic Granite facies of the Alto de São Bento granitic suite, with characteristic K-feldspar phenocrysts commonly showing concentric zoning (zoomed-in photo also shown); large biotitic enclaves and thin pegmatitic veins (photo from the authors). (b) Scenery over the Évora UNESCO City at the Alto de São Bento Area (photo from the authors). (c) Drone imagery over the Almendres Dolmen Complex (photo from the authors). (d.) Overview of the migmatite outcrop at the Almansor riverbed (photo from the authors). (e.) Example of the diatexite, metatexite and restite structures individualized in the Gneiss-Migmatite Complex at the Almansor river (photo from the authors). (f.) Photography showing geological features characteristic of the karst system inside of the Escoural Cave. This photography is a courtesy from the Direção Regional de Cultura do Alentejo (DRCA; Regional Direction of Alentejo´s Culture).

Figure 4

Serra do Conde Quarry representative features and A-B cross section shown in Figure 1. (a) Wall of the front of quarry exploration in which exceptional outcrops of the gree-amphibolites of the Carvalhal Formation are observed (photo from the authors). (b) Close-up photography of the Carvalhal Formation amphibolites at the Serra do Conde Quarry, with clear Epidote development marks the S_0 foliation, later folded and marking a second stage of deformation (S_1) (photo from the authors). (c) A-B cross section representative of the Serra do Conde area. The A-B profile is shown in Figure 1 as was adapted from Silva (2013).

Figure 5

Digital elevation model with overlapped ortophotomaps of the Vale da Arca Mine and Quarry area, which is the result of drone aerial imaging and latter 2.5D model construction using QGIS plugin QGIS2ThreeJS. The pinpoints on the model correspond to locations where several geodiversity features can be observed. These locations are described throughout the manuscript.

Figure 6

Main geodiversity features of the Vale da Arca Mine and Quarry area. (a) Boudinage of a siliceous bedding parallel to the surrounding marbles at the Vale da Arca area. The boudains mark the main deformation direction (NNW-SSE) (photo from the authors). (b) Inter-boudain structures observed in the marble units (photo from the authors). (c) Necking boudinage structures observed in the marble units and marking the deformation direction (photo from the authors). (e) Close-up photography of a metavolcanic intercalation on the marble units, where individualization of large feldspar, epidote, amphibole and calcite crystals is possible (photo from the authors). (f) Photomicrograph of a cross-section prepared from the magnetite ore bodies of the Vale da Arca mine, with porous rims (red rectangle) (photo from the authors). (g) Electron Dispersive Spectroscopy mapping showing Si, S, Ca, Fe and Zn distribution of the section shown in the red rectangle from (f). The SEM-EDS mapping allowed to identify the mineral phases observed in the porous rims of the magnetite crystals.

Figure 7

Main geodiversity features of the Monges Mining Complex. (a) Abbey at the Monges Mine, which gives the name to the mine and was used to lodge the miners (drone photo from the authors). (b) Euhedral crystals of magnetite on massive magnetite ore bodies, which are observed at the outcrops of the open pits at the Monges area (photo from the authors). (c) Example of one of the open-pit mining area at the Monges Mine (photo from the authors). (d) Oxidation processes of the magnetite-pyrite ores (photo from the authors). (e) Photomicrograph of a cross-section prepared from the magnetite ore bodies. (f.) Identification of micrometric inclusions by backscattered electron imagery.

Figure 8

Proposal of geodiversity routes between the Évora and Montemor-o-Novo Municipalities. The proposed routes are idealized to create a Geodivertisy "Bridge" between these two historical cities. The marked locations correspond to the geodiversity sites and geosites described throughout the manuscript; the base map was constructed from QGIS using the Ortophotomap from Open Street View.

Supplementary Files

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- SupplementaryMaterialA.xlsx