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ORIGINAL PAPER

The *Escarpão* Plateau (South of Portugal)—a Study Case of Nested Geosites from the Aspiring Algarvensis Geopark

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Abstract

Located along the southern limit of the Algarvensis aspiring UNESCO Global Geopark (aUGGp), the *Escarpão* Plateau is a singular geomorphological structure sculpted by fluvial, karst, and tectonic processes. The plateau is deeply scarved by the *Quarteira* Rivulet, forming a valley that crosses the most complete Upper Jurassic sedimentary sequence of the Eastern Algarve (Southern Portugal). This sequence includes five geological formations representing different depths of carbonate ramp deposition from the Tethys Sea: *Peral* Formation, *Jordana* Formation, *Cerro da Cabeça* Formation, *Escarpão* Formation, and the upper Limestone Formation with *Anchispirocyclina lusitanica* (foraminifera), respectively from the oldest formation to the most recent at the top. Throughout the Quaternary Period, the karst processes shaped a landscape of sparse and poor soils, based on which successive generations adapted their subsistence agriculture and way of life. The geomorphology of the plateau and the rivulet valley, the sequence of the carbonated formations, and the diversity of sedimentary and paleontological records can be considered possible sites of diverse geological interest and with different scales that are embedded in each other, forming thus nested sites. To promote and preserve these sites, the Algarvensis aUGGp shaped an 8-km-long interpretative walking path, passing through 11 points of interest, including biosites and geosites. Their interpretative boards highlight not only the different spatial and temporal geological diversity but also its relationship with surrounding cultural and historical heritage. Finally, this work allowed the creation of new products for outreach and public awareness towards an effective geoconservation.

Keywords Algarve · Aspiring Geopark · Algarvensis · Geosites · *Escarpão* Plateau

Introduction

The Algarve is the southernmost region of Portugal mainland, famously known for its beautiful beaches, mild climate, peaceful environment, and tasty Mediterranean food. Being one of the most visited regions for sun and beach tourism in Europe (European Union 2022), its coastal zone became a densely populated area with intensive urban growth and significant touristic income (Mendes et al. 2011), while the inland part of the region has been abandoned and neglected both by people and stakeholders. The Algarve presents thus a highly contrasted reality, being a rich region according to European statistics, although it includes several parish areas of low-density population index and low incomes (CCDRAlgarve 2022). It is important to note that one of the main attractions of coastal Algarve area lies in its wide diversity of geological processes and structures, such as carbonate abrasion platforms, sinkholes, faults and dykes, cliffs with stratified multicolor layers ranging from flysch sequences to limestones, calcarenites. and siltstones. These features tell the story of several million years of Earth's History (e.g., Moura et al. 2006).

Of course, this significant geodiversity is not limited to the coast but also present inland, representing a unique opportunity for a sustainable development strategy in this declining area, based on cultural and natural tourism. This opportunity arose thanks to the discovery of the new species

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Metoposaurus algarvensis (Brusatte et al. 2015), belonging to the Temnospondyl amphibians, in the inner Algarve region. This discovery led to a project aiming at the creation of a UNESCO Global Geopark (UGGp).

Accordingly, in 2018, the municipalities of Loulé, Silves, and Albufeira, together with the University of Algarve and its Centre for Marine and Environmental Research, presented their intention to become a UNESCO Geopark, giving birth to the project of the Algarvensis aspiring UNESCO Global Geopark (aUGGp) (www.geoparquealgarvensis.pt).

Being the southernmost of all Portugal mainland UGGp and aspiring geoparks (Fig. 1), the Algarvensis aUGGp territory covers close to a third (1381 km^2) of the Algarve region. It mainly encompasses the *Baixo Alentejo* flysch group formations from the Paleozoic and the carbonated formations from the Ceno-Mezosoic (Fig. 2) (Terrinha et al. 2006), representing a wide time interval of Earth's history. This very high geodiversity is represented by a variety of sites whose values are being identified, assessed, and compiled through a detailed inventory (Campos 2021; Oliveira et al. 2021a, 2021b; Rodrigues et al. 2021; Veiga-Pires et al. 2019).

In the present work, we focus on the *Escarpão* Plateau study case, which is the first work completely developed under the Algarvensis aUGGp strategic project and includes

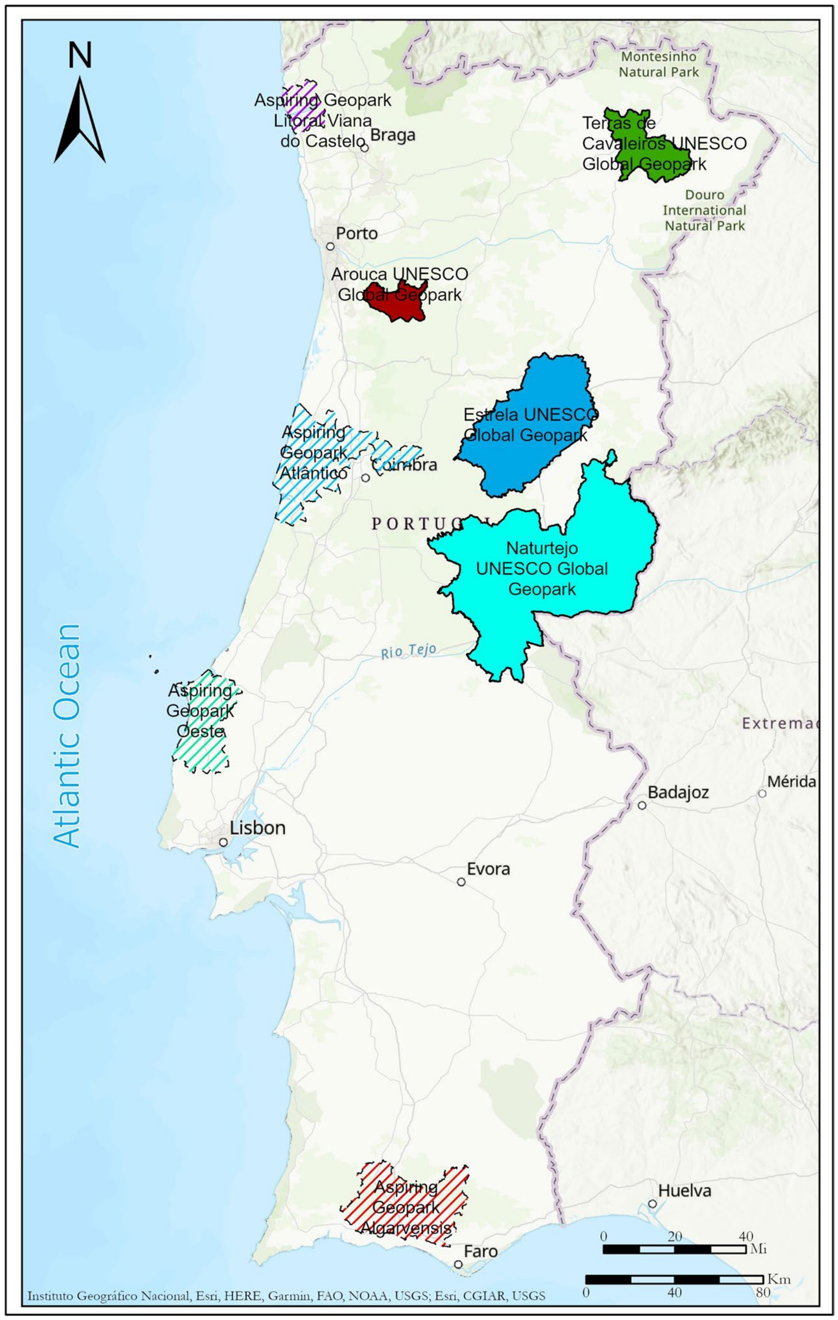

Fig. 1 UNESCO Global Geoparks (plain) and aspiring Geoparks or projects (stripped) from north to south mainland Portugal: Viana do Castelo aUGGp (stripped purple), Terras de Cavaleiros UGGp (green), Arouca UGGp (burgundy), Estrela UGGP (blue), Atlantic Geopark project (stripped blue), Naturtejo UGGp (cyan), Oeste aUGGp (stripped green) and Algarvensis aUGGp (stripped burgundy)

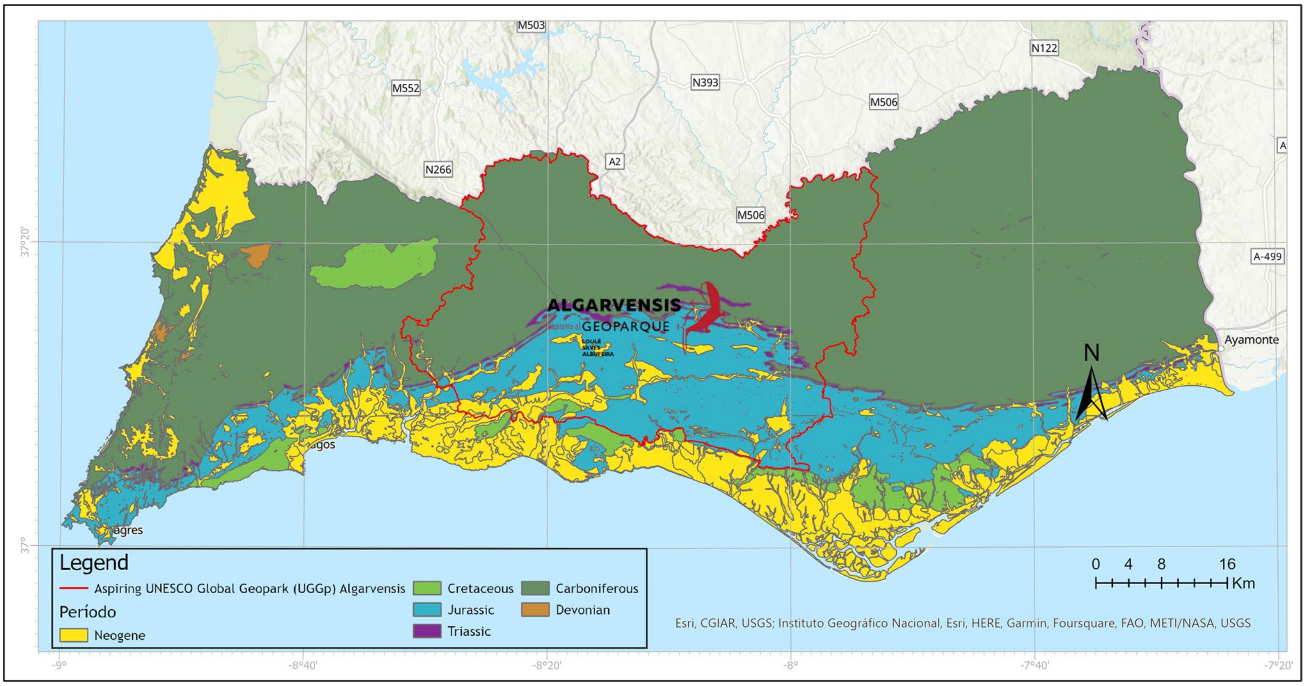

Fig. 2 Simplified geology of the Algarve Region with the limits of the Algarvensis aspiring UGGp (red line), based in the geological map 1/100 000 edited by the Geological Services of Portugal. After Manuppella 1992

the main subjects of concern: scientific knowledge, educational awareness and training, cultural and sustainable tourism. We will first present the general geomorphological setting of the Algarve region, focusing on the Meso-Cenozoic Algarve Basin, and then more specifically on its Upper Jurassic sequence which forms the *Escarpão* Plateau. We will then present the outputs resulting from the intensive bibliographic and fieldwork scientific study presented here, such as the (paleo)environmental evolution of the area, the proposed geodiversity points of interest, and the short walking route with its interpretative panels and digital supporting information.

Study Area

The study site is in the southern part of the Algarvensis aUGGp, whose territory occupies the central part of the Algarve region (Fig. 2). The region's geomorphology is organized in bands parallel to the actual coastline and approximately E-W (Fig. 2), denoting four main phases of paleogeographic evolution. To the north, the mountains represent a morphologically monotonous relief deeply dissected by a dense drainage network, with rounded crests at similar heights of approximately 470 m. Being part of the Hesperic Massif, they are composed by impermeable Paleozoic rocks, mainly shales and greywackes, that favor surface runoff at the expense of infiltration. During the Upper Cretaceous, an intrusive structure gave rise to the Monchique Mountain, culminating at 902 m and composed of nepheline syenites that intruded the Paleozoic rocks.

The Upper Triassic polygenic complex formed by reddish sandstones, mudstones, and evaporitic deposits (Fig. 2) outcrops on this mountain's southern border, in unconformity with the underlaying Paleozoic folded rocks. Those sediments of fluvial and lagoonal origin are intersected by volcanic rocks, which belong to the Central Atlantic Magmatic Province and constitute a testimony of the first rifting phases of the Tethys Ocean (Early Jurassic, ca. 201 million years; Fernandes et al. 2014).

Further south lies the *Barrocal* (meaning "chaos of blocks") subregion mainly composed of Jurassic and Cretaceous limestones, dolostones, marly limestones, and marls (Fig. 2). It contrasts with the quite uniform relief of the Paleozoic mountains, regionally called the *Serra* (meaning "mountain") subregion. The observed asymmetry of the *Barrocal* relief results from the conjugation of remarkable differences in rock hardness and a scarce drainage network, as water easily infiltrates into the karstic terrains to feed extensive aquifers (Terrinha et al. 2006).

These Mesozoic and Cenozoic units compose the so-called sedimentary Algarve Basin, which includes the Triassic-Cenomanian sedimentation structurally governed by a rifting phase (splitting apart of tectonic plates) and the Cenozoic post-rifting phase (Terrinha et al. 2006).

During the Sinemurian, the Algarve Basin was structured into two sub-basins, west and east from the structural high

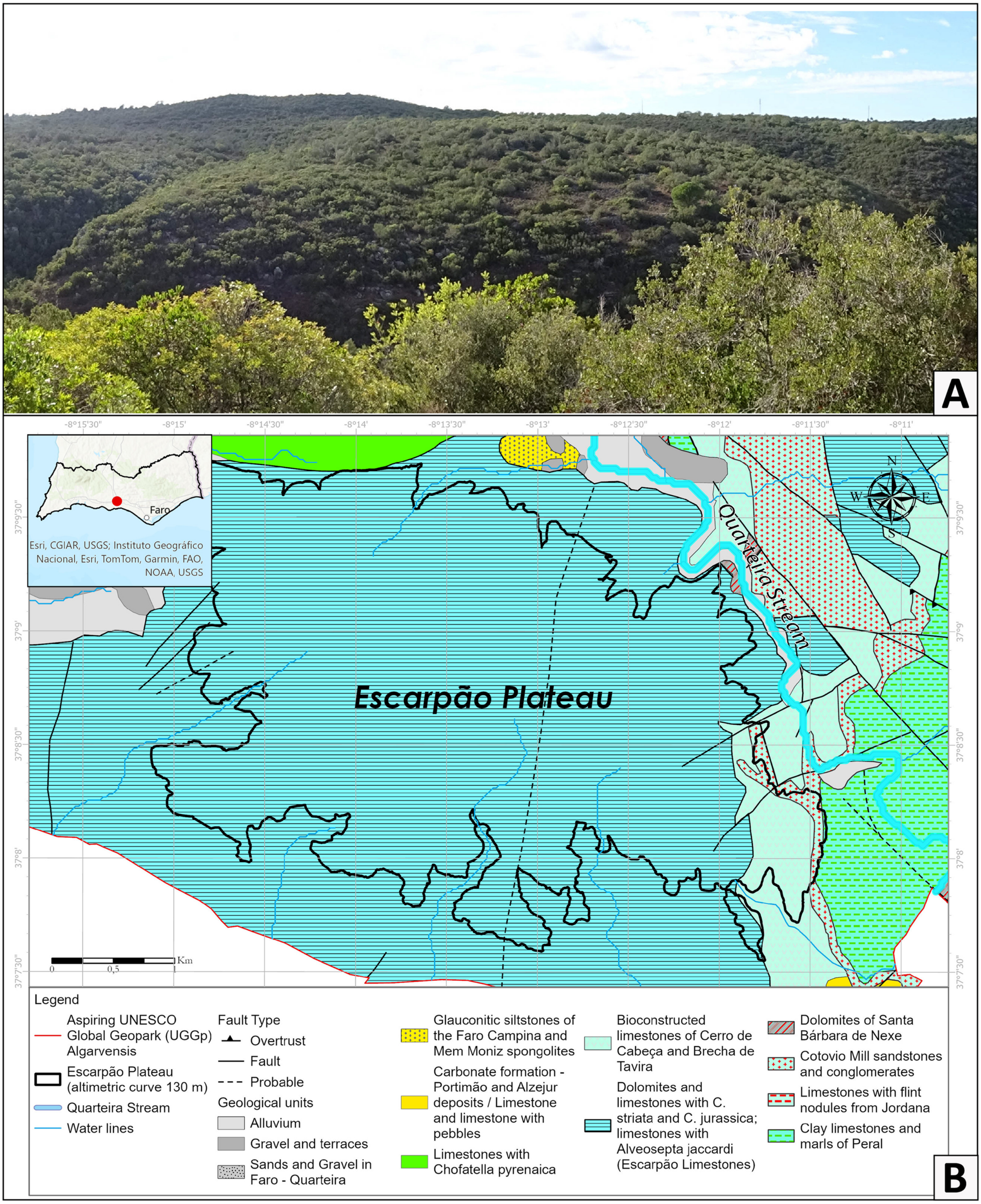

Fig. 3 Picture of the Plateau landscape (**A**), photo © Moura; location, limits, and lithology of the *Escarpão* Plateau (**B**). After Moura and Oliveira (2022)

of *Budens-Algoz,* respectively. During the Lower and Mid Jurassic (approximately 201-163 million years), sedimentation in the western sub-basin evolved into deeper marine conditions than in the eastern sub-basin. However, the eastern sub-basin underwent subsidence throughout the entire Jurassic period, leading to the accumulation of thicker sequences than in the western sub-basin (Terrinha et al. 2006; and all here cited). The *Escarpão* Plateau, structurally bellowing to the eastern Jurassic sub-basin (Figs. 2 and 3), exposes the most complete sequence of the Upper Jurassic of the eastern Algarve.

The *Escarpão* Plateau Geosite

The *Escarpão* Plateau is defined as a geomorphological flat surface of approximately 13.48 km^2, with its border corresponding to the 130-m altimetric curve (Fig. 3). Due to its distinctive scientific value, this geomorphological landscape is considered as a geological heritage site, or geosite, meaning an "in situ occurrence of geodiversity elements with high scientific value" as presented in Brilha (2016). These elements constitute part of the geological heritage, together with geological elements preserved in museums, referred to as geoheritage elements.

In the following paragraphs, we describe the different geological elements that are present at different observational scales in the geomorphological structure of the *Escarpão* Plateau geosite, forming what we call "nested geosites." Some of the sites presented hereafter can also be considered geodiversity sites, instead of geosites, considering that they are "in situ occurrences of geodiversity elements with other values than scientific," such as educational, touristic, or aesthetic (Brilha 2016). Thus, they are points of geological interest but not geoheritage sites than deserve to be conserved.

A. *Escarpão* Landscape

The summital surface of the Escarpão Plateau runs at approximately 130 m high and corresponds to a karst flattening, mostly from a karren phase, with some sinks, dolines, and lapiaz (Fig. 4). To our knowledge, large and deep sinkholes and caves are rare (Regala 2021). This is not surprising in a semi-arid region receiving approximately 400–700 mm of precipitation per year onto a carbonate substrate (Dias et al. 2019), which privileges infiltration to surface runoff.

The plateau is deeply incised by the *Quarteira* Rivulet with a NW-SE orientation structurally controlled by the *Quarteira* fault (Fig. 3). Several tectonic and eustatic fluvial terraces can be seen along the valley (Fig. 5), resulting mainly from downwearing geomorphic mechanism. In contrast to this vertical erosion, backwearing has not yet been enough to produce a large valley with fluvial beaches, although we find fertile floodplains at the confluence with two tributaries at the base of the plateau (Fig. 6).

However, the definition of landscape is no longer only centered on geological structures, processes, and time, as postulated by Davis (1899) and by the United Nations (Mitchell et al. 2009) almost one century later. At present, humans and their activities are integral part of some landscapes, producing rapid and significant changes to them, but also maintaining an interaction with natural systems, forming a distinctive landscape defined by UNESCO as cultural landscapes (Mitchell et al. 2009).

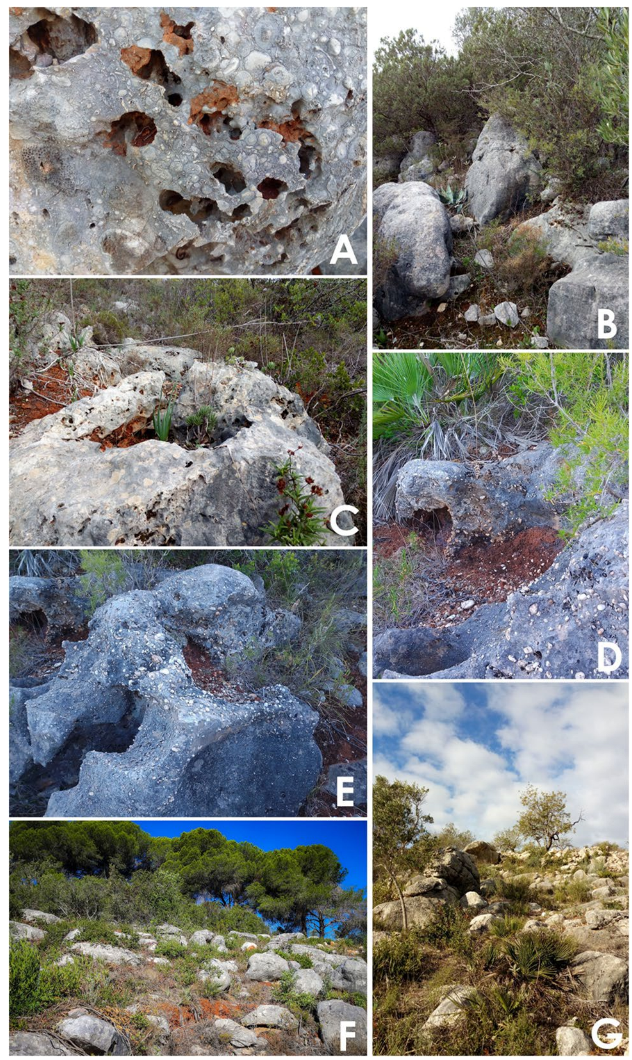

Fig. 4 Field photographs with examples of some aspects of the epikarst morphology of the *Escarpão* Plateau: secondary porosity resulting from the dissolution of carbonate fossils (**A**); *Terra Rossa* (reddish sediment in the dissolution troughs) resulting from the limestone dissolution (**B**–**E**); lapiaz landscape (chaos of blocks) (**F**, **G**). Photos © Moura and Oliveira (2022)

Here, the rural population linked to the Escarpão plateau is concentrated in small villages, with *Paderne* being the largest one, with approximately 3500 inhabitants and a density of 66 inhabitants per km^2 (INE Statistics Portugal 2022). The main activity of the people from this economically and demographically depressed region was once non-extensive agriculture. Old agricultural houses, irrigation channels, wells and norias (hydro-powered scoop wheel) take us to a not-too-distant past when cereal crops and rainfed orchards were the main economic activity on the plateau and surroundings (Fig. 7).

Apart from the above-mentioned floodplains (see Fig. 6), the reddish soil on the plateau is mainly composed of *Terra Rossa*, characteristics of the poor and thin soils of Mediterranean type (Verheye and de la Rosa 2005). However, local populations never surrendered to this morphoclimatic unfavorable context for agricultural practice, mostly subsistence agriculture. The magnificent network of dry stonewalls (without any binder between the stone blocks), resulting from the removal of stones from the terrain, that for generations sustained the soil against erosion and divided properties, is a beautiful landscape component of the plateau (Fig. 7).

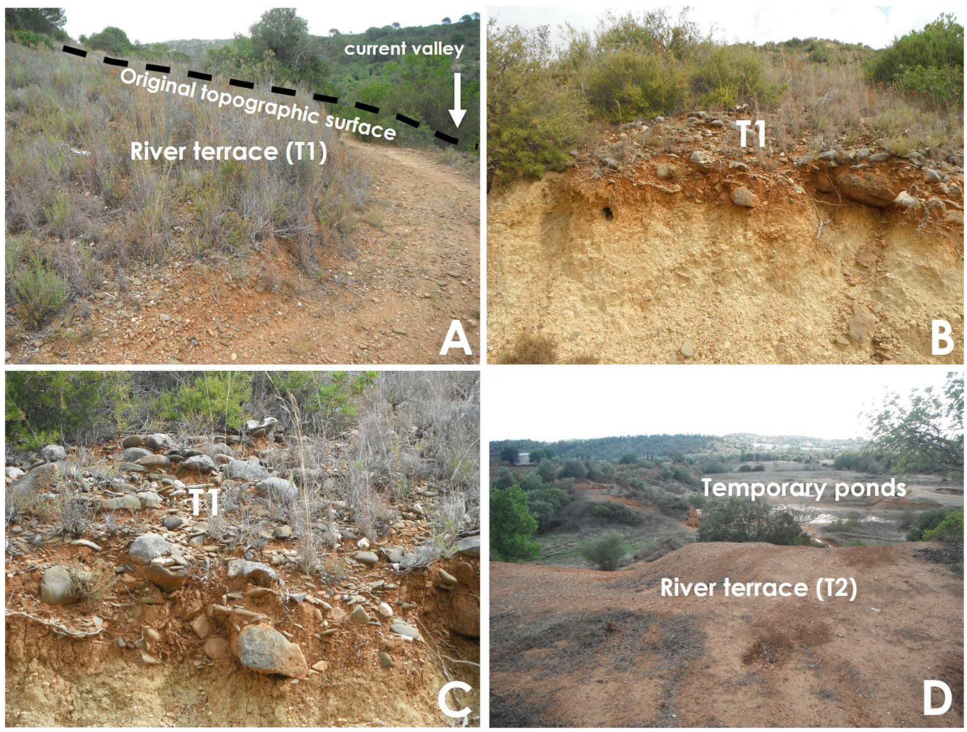

Fig. 5 Fluvial terraces of the *Quarteira* fluvial system: river terrace (T1) located on the left bank of the *Ribeira de Quarteira*, about 5 to 10 meters above the current bed (**A**–**C**). The dashed line in A represents the original topographic surface when the rivulet deposited the alluvium; fluvial terraces (T2) of the *Algibre* stream, near *Paderne* (in the background in photo D) and Mediterranean Temporary Ponds (priority habitat 3170 - habitat directives 92/43/EEC) (**D**). Photos © Moura and Oliveira (2022)

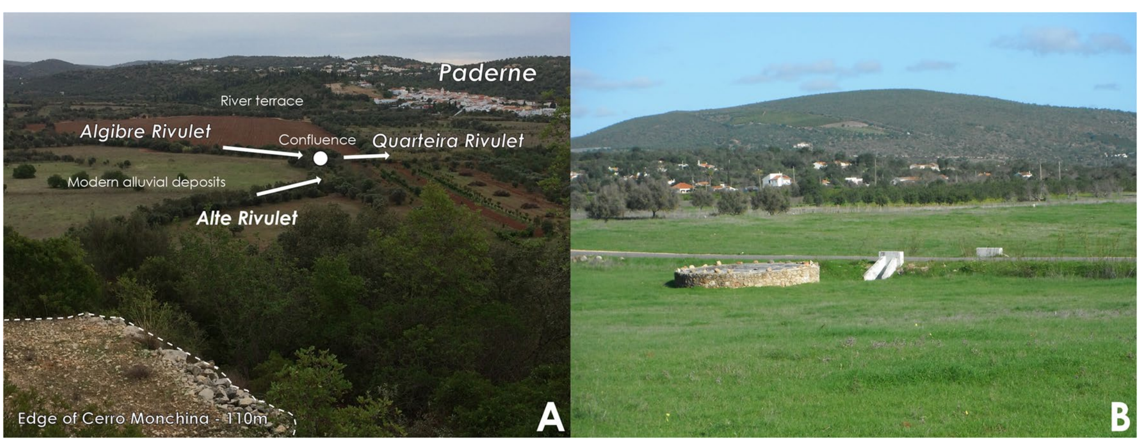

Fig. 6 Floodplain located at the confluence of *Algibre*, *Alte* and the mainstream *Quarteira* Rivulet (**A**); floodplain (modern alluvial fans) (**B**). Note the water-conduit dike, a constant in these landscapes where the exploitation of scarce surface water resources is vital. Photos © Moura and Oliveira

Fig. 7 View to stone-walled terraces (**A**); dry stonewalls, a remarkable aspect of the plateau landscape, testimonies of an effort over generations (**B**). Photos © Moura and Oliveira (2022)

B. Tethys Ocean's heritage: a tropical carbonated ramp

The geological formations of the *Escarpão* Plateau were deposited during the Upper Jurassic in a homoclinal carbonated ramp (a type of continental shelf) from the Tethys Ocean. The depth of the water on the shelf was successively reduced from the older stratigraphic unit, the *Peral* Formation (Oxfordian), to the more recent one, the limestones' Formation with foraminifera species *Anchispirocyclina lusitanica* (Egger 1902; Tithonian) (Figs. 8 and 9).

This Oxfordian-Tithonian sequence is the most complete stratigraphic sequence that can be observed in the eastern Algarve subregion, thanks to the incision of the *Quarteira* rivulet into the plateau (Ramalho 2015). The detailed description of this sequence follows below, from the oldest and deeper marine paleoenvironment formation to the youngest and shallowest one.

The *Peral* Formation corresponds to sedimentary deposition over approximately 6 million years (Ma) along the ramp external domain of the Tethys continental margin's pelagic domain (Figs. 8 and 9), when Europe was only a set of islands. This formation is composed of ~200 m thick marl deposits interlayered with marly limestones. The macrofossil content, dominated by ammonites and belemnites, and the microfossil content, which includes coccolithophorids and dinoflagellates (single celled organisms of the marine plankton), are compatible with the external domain of the carbonate ramp (Fig. 9).

The overlaying *Jordana* Formation was deposited in a shallower environment of the ramp, receiving strong terrigenous input (minerals and rock fragments) (Fig. 9). This formation is indeed mainly composed of reddish sandstone displaying cross stratification, hummocky stratification, and positive grading (Fig. 10). These attributes, together with the rare broken macrofossils, are common in mid-oceanic ramps influenced by storms (Pomar 2020). The terrigenous character of this formation is probably the result of a wet climatic phase, which promoted erosion over the continental area. However, the decrease in water depth relative to the time interval of the *Peral* Formation deposition must be related to a regressive phase of sea level or a continental uplift. The latter hypothesis is supported by the basal conglomerate, which indicates a strong initial erosional phase (Fig. 10) and by the mean sea level transgressive tendency during the Upper Jurassic (Hallam 2001; Haq 2017).

The carbonate ramp underwent continuous and progressive shallowing throughout the Kimmeridgian and Tithonian, with coral reef construction leading to the *Cerro da Cabeça* and *Escarpão* formations (Fig. 8). The macrofauna in these formations includes fossils of corals, sponges, stromatoporoidea, crinoids, rudists, gastropods, and bivalves. The diversity of microfossils such as foraminifera and phytoplankton is also high. The foraminifera *Alveosepta jaccardi* (Schrodt 1894) found in *Cerro da Cabeça* formation is assumed to be a biostratigraphic proxy for the end of the Oxfordian-early Kimmeridgian in the Tethysian basin (Sarfi and Yazdi-Moghadam 2016).

The microfossil species richness reaches its maximum value in the *Escarpão* Formation (Kimmeridgian-Tithonian; ca. 153.3-152.1 Ma), which also has the higher vertical facies variation among the formations exposed in the slopes of the *Quarteira* rivulet valley. However, its reef macrofossil content is equivalent to the fossil content of the *Cerro da Cabeça* Formation. The transition between these two formations is marked by an oolithic facies, which is a sedimentary proxy of shallow waters (Fig. 9). Together with the occurrence of large benthonic foraminifera, this supports the proposed depositional paleoenvironment for the *Escarpão* Formation as a shallow carbonate ramp of tepid water.

Considering the extensive occurrence of coral remains and other reef organisms on top of the plateau, the barrier

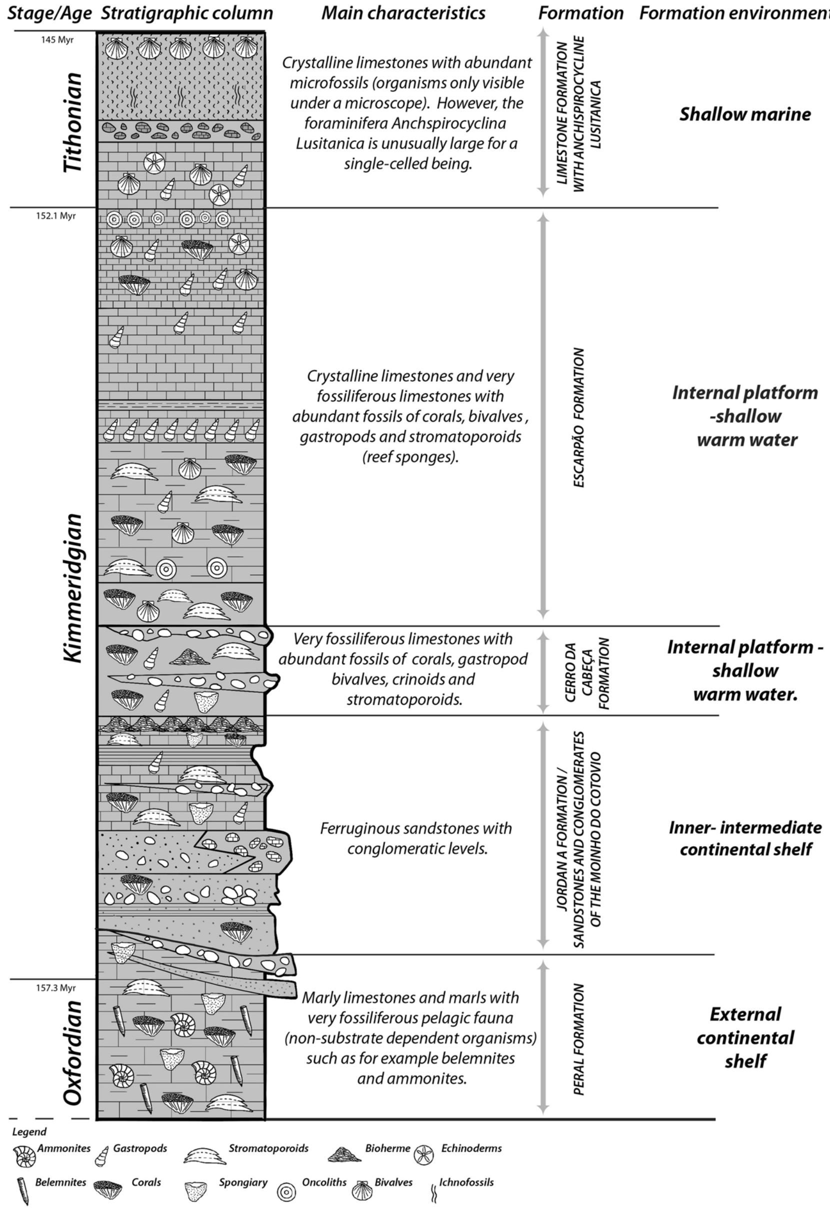

Fig. 8 Lithostratigraphic column representing the formations that composed the substrate o the plateau. After Moura and Oliveira (2022)

reefs would probably have occupied a vast area and remained active for approximately 5.2 million years, corresponding to the depositional time interval of *Cerro da Cabeça* and *Escarpão* formations. However, to our knowledge, coral reefs in life position do not occur on the plateau, except for two blocks, meaning that bioerosion and weathering have been very efficient in destroying the barrier reefs.

Finally, the limestone formation with *Anchispirocyclina lusitanica* (Egger 1902; see Fig. 8 and 9) represents the last continental shelf sedimentation before its emergence, probably due to continental uplift or a lowering of the mean sea level. The unusually large benthonic foraminifera *A. lusitanica* (Egger 1902) is a rare Upper Jurassic age fossil in Portugal, marking the transition from Jurassic to Cretaceous (Upper Kimmeridgian – Berrasian; ca. 145- 139.8 Ma) and characterizing very shallow to continental transitional environments.

In view of the above, the sedimentary facies architectures in the Algarve during the Mesozoic (ca. 252-66 Ma) seem to have been controlled by regional tectonic, probably related to halocenese that produced compartments of different marine water depths. In combination with the mean sea level changes and continental rise pulses, this resulted in contemporaneous different lithofacies and biofacies (Moura and Oliveira 2022). Nevertheless, the sequential analysis of the formations and their lateral variations exposed on the *Escarpão* Plateau strongly suggests a sedimentation environment of a marine carbonate ramp evolving successively from the deepest domain in the Oxfordian (*Peral* Formation) to mid domain (*Jordana* Formation), to barrier reefs from the internal ramp (*Cerro da*

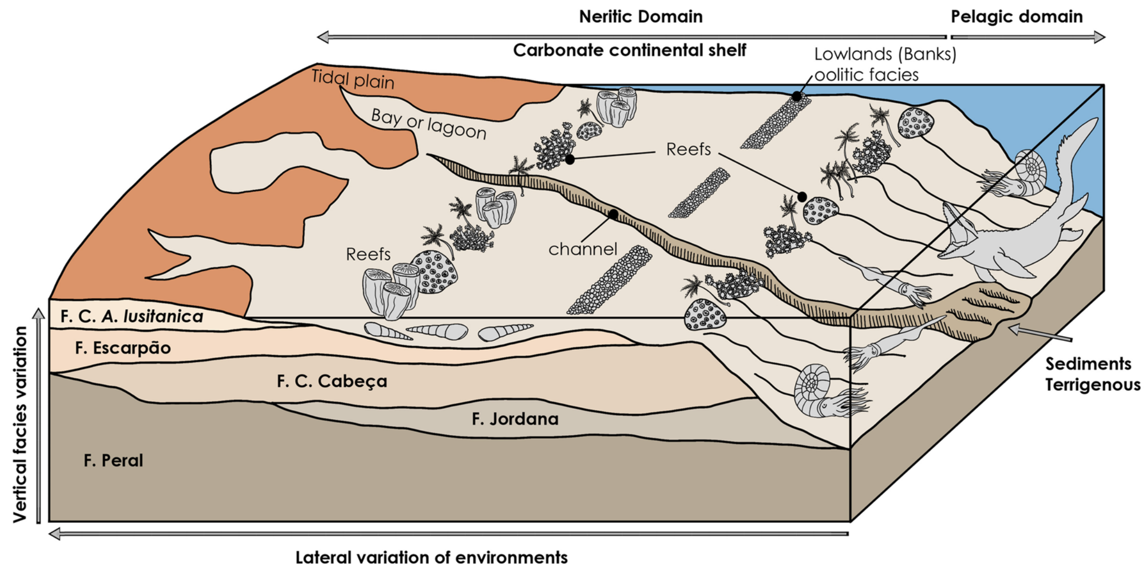

Fig. 9 Schematic representation of the carbonated ramp where the formations of the Escarpão Plateau were deposited. After Moura and Oliveira (2022)

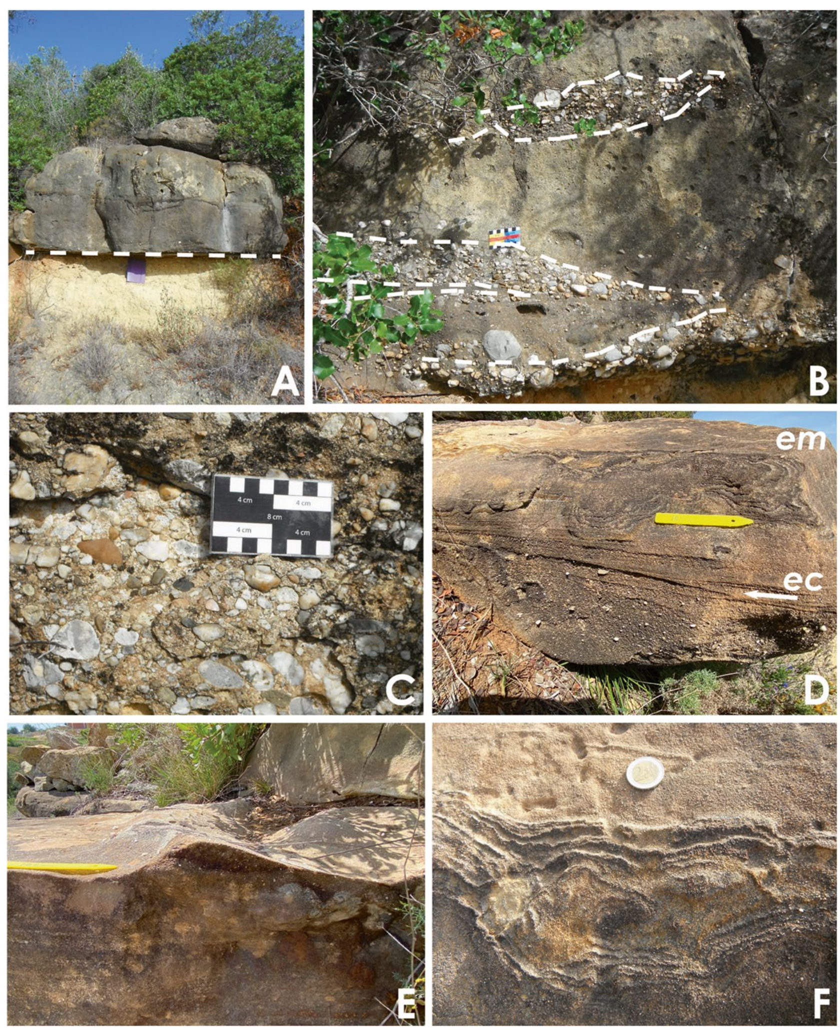

Fig. 10 Sedimentary features of the *Jordana* Formation: contact between the *Peral* (P) and *Jordana* (J) formations (**A**); cross-stratification in the *Jordana* Formation and basal conglomerate (**B**); detail of the conglomerate at the passage from the *Peral* Formation to the *Jordana* Formation (**C**); cross-stratification (ec) in the sandstones of the *Peral* Formation and microbial structures (em) (**D**); ripple marks (**E**); elephant-skin microbial structures (**F**). Photos © Moura and Oliveira (2022)

Cabeça and *Escarpão* Formations), and to confined marine environment (limestones with *A. lusitanica* (Egger 1902)) in the Tithonian (152-145 Ma) (Moura and Oliveira 2022).

The *Escarpão* Plateau Sites of Interest

As presented above, the *Escarpão* Plateau has high geological interest, not only due to its scientific values, but also because of its educational, touristic, and aesthetic. It was important to complement and detail the *Escarpão* Plateau complex geosite with a spatial-scale approach (Brocx and Semeniuk 2007; Forno et al. 2022), from the landscape (kilometers) to local (tens to hundreds of meters) and outcrop (centimeters to meters) sites of interest, to raise awareness of its geodiversity and initiate a geoconservation strategy.

The detailed inventory started by a meticulous review of the existing literature and site descriptions to recover the exact locations in the field. This phase turned out to be quite difficult since most of the references did not have exact georeferentiation. However, no unique local or outcrop permitted the observation of the entire Upper Jurassic sequence, and thus exhaustive fieldwork had to be carried out. This second phase led to the recognition of more than 40 points of interest, including geodiversity elements, cultural, and biodiversity sites. The choice of the final sites considered the conjunction of several variables: accessibility, the balance between conservation and awareness, the need to have a circular route within public domain, or with authorization from private landowners, and the representativeness of the sites.

Accordingly, eleven sites (five geosites, four geodiversity sites, and two biodiversity sites, Table 1) with different scales have been identified along an 8-km-long walking route with interpretative panels (Fig. 11) and characterized based on their scientific, educational, cultural, or aesthetic significance. This walking route will allow the visitors to travel along 163 million years of local geological history and is now registered and recognized by national pedestrian entities as PR4 - small route from the Albufeira Council (Fig. 11).

Site 1–Diving in the Deep Sea: Peral Formation

Located at the bottom of the *Quarteira* rivulet valley, this local-scale geosite lies on the *Peral* Formation, deposited on the continental shelf of the Tethys Ocean, and displays several molds of ammonites and belemnites (Fig. 12). The marls of the *Peral* Formation underwent at least two phases of soil formation (pedogenesis). The oldest took place during a dry climatic phase, with an evaporation rate higher than the precipitation rate, forming whitish soils designated as caliches (Fig. 13). During a subsequent humid climatic phase, precipitation induced sufficient water percolation into soils

Table 1 List of the eleven nested sites from the *Escarpão* Plateau that have been chosen for the storymap (https://arcg.is/f95KD) and the interpretative panels along the PR4 walking route (Fig. 11)

Name	Site no.	Value	Inventory[1]	Scale[2]
Diving in the Deep Sea: *Peral Formation*	1	**Scientific** *Educational*	*Geosite*	*Local*
When the Climate was more Humid: *Jordana* Formation	2	**Scientific** Educational	*Geosite*	*Local*
Diving in Coral Reefs: *Cerro da Cabeça* and *Escarpão* Formations	3	**Scientific** Educational Aesthetic	*Geosite*	*Local*
Escarpão Plateau: genesis and evolution	4	**Scientific** Educational Aesthetic	*Geosite*	*Landscape*
The Water That Feeds Aquifers: Fields of Sinks	5	Educational Aesthetic	*Geodiversity site*	*Outcrop*
Escarpão Plateau Biosite	6	*Biodiversity*		
The *Escarpão*'s karst	7	Educational Aesthetic	*Geodiversity site*	*Local*
Alluvium of the *Quarteira* rivulet	8	Educational Aesthetic	*Geodiversity site*	*Local*
Quarteira Rivulet Biosite	9	*Biodiversity*		
Terraces of the *Quarteira* rivulet	10	**Scientific** Educational	*Geosite*	*Outcrop*
The Floodplains - Water Use	11	Educational Aesthetic	*Geodiversity site*	*Local*

[1]Inventory type as proposed by Brilha (2016).

[2]Scale of the geoheritage feature as proposed by Brocx and Semeniuk (2007)

Fig. 11 Front page (**A**) and map of the PR14 walking route path with the eleven locations (**B**) corresponding to either Landscape/scenic, local or outcrop sites, and four geosites, five geodiversity sites and two biosites, described on in-situ panels (**C**) and in the main text below

and rocks to mobilize iron. However, due to its poor solubility, this iron precipitated, giving the soil a red color (Fig. 13).

Finally, the karst flattening, resulting from limestone weathering, created flattened areas of different dimensions, locally known as *chãs* (Fig. 13). These flattened areas contain the rare suitable soils for agriculture in the *Escarpão* plateau, apart from the rivulet alluvium, often used to support for cereal crops.

Site 2—When the Climate Was More Humid: Jordana Formation

This local-scale geosite represents the contact between the *Peral* and the *Jordana* Formations (Figs. 10 and 14) and offers a scenic view on the stone-walled terraces (Fig. 7).

The *Jordana* Formation (Fig. 8) is distinguishable from the *Peral* Formation due to its coarse detrital character and rarity of fossils (Fig. 14). The *Jordana* Formation has a lateral contemporary equivalent formation, the *Moinho do Cotovio* Sandstone and Conglomerate Formation, representing different sedimentary environments (Fig. 9).

The *Jordana* Formation sandstones were deposited on the Tethys intermediate continental shelf affected by maritime storms, remobilizing the sediments, and inducing cross-bedding features and positive gradation (Fig. 15), whereas the *Moinho do Cotovio* Sandstones and Conglomerates are fluvial in nature. A notable feature of the *Jordana* Formation is the frequent microbial structures that resemble an elephant's skin (Figs. 10 and 15).

Site 3—Diving in Coral Reefs: Cerro da Cabeça and Escarpão Formations

This local-scale geosite exemplifies the *Cerro da Cabeça* Formation deposited on the internal continental shelf with a luxurious life, including corals, crinoids, sponges, bivalves, and gastropods, which constituted a reef ecosystem (Fig. 16). The reefs were totally or partially destroyed by storms, as evidenced over a vast area by the numerous and dispersed coral blocks and fragments, rarely found in a living position (Fig. 17). This chaos of blocks also favored the development of lapiaz over the area (Fig. 18).

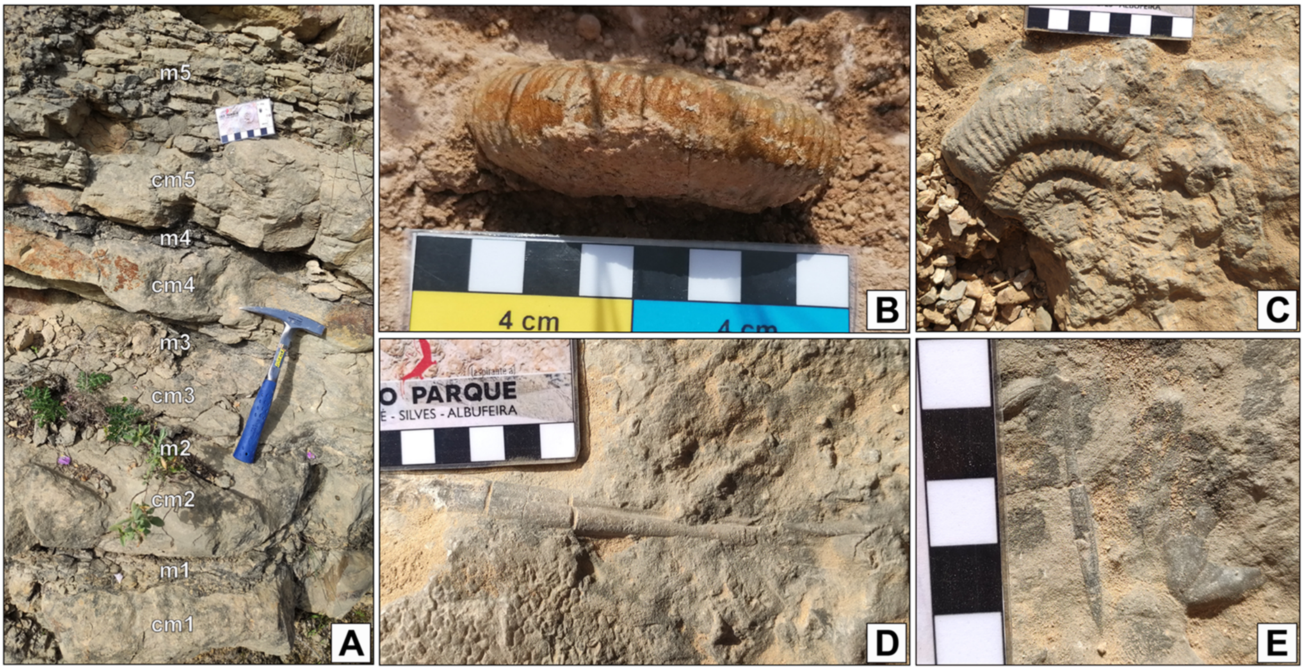

Fig. 12 Outcrop of the *Peral* Formation, consisting of a succession of marls (m) and marly limestones (cm) (**A**); Fossils that can be found in the slabs and stones, such as ammonite molds (**B** and **C**) and belemnite rostrum (**E** and **F**). Photos © Moura and Oliveira (2022)

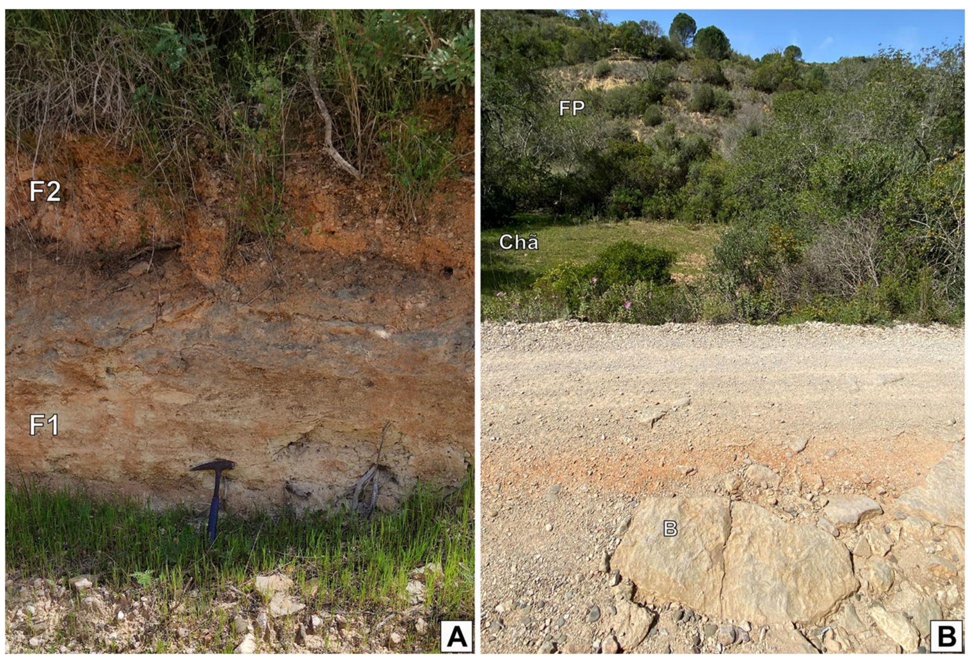

Fig. 13 Soil, developed on *Peral* Formation rocks (**A**), generated in two distinct climatic phases: Phase 1 (F1)- dry; Phase 2 (F2): humid. Surrounding morphological aspects (**B**). FP, *Peral* Formation; Chã, Flat; B, block with bioturbation and rostrums of belemnites (cephalopods). Photos © Moura and Oliveira (2022)

Site 4–Escarpão Plateau: Genesis and Evolution

Site 4 presents a panoramic view of the singular geomorphological entity of the *Escarpão* Plateau landscape-scale geosite, shaped along many millions of years by combined fluvial, karst and tectonic processes (Fig. 19). This landscape was produced through several stages of various processes, such as variations in mean sea level, vertical movements of the Earth's crust, deformation, and alteration of rocks (Moura and Oliveira 2022).

As mentioned above, the *Escarpão* Plateau's limestone substratum is the result of the accumulation of marine sediments on the Tethys Ocean seabed throughout the Upper Jurassic (Figs. 9 and 19). The fragmentation of the

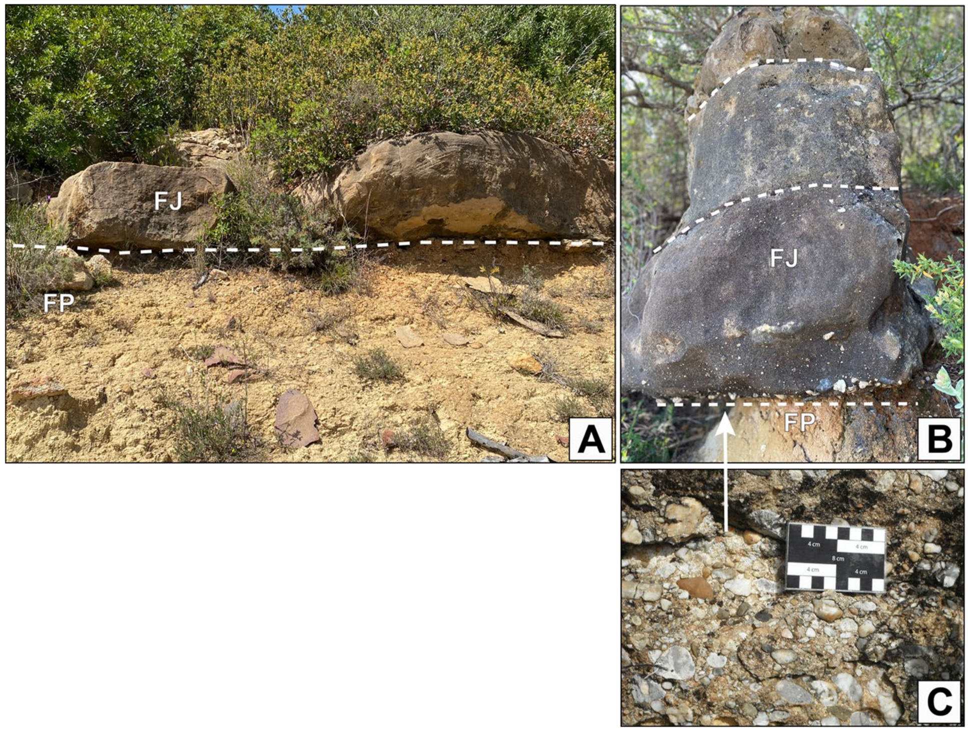

Fig. 14 Contact between the *Peral* (FP) and *Jordana* (FJ) Formations, marked by a white dashed line (**A**). Contacts between layers are also marked with dashed white lines (**B**). Note the conglomerate (quartz pebble, quartzite, and greywacke) in the transition between the two formations (**C**). Photos © Moura and Oliveira (2022)

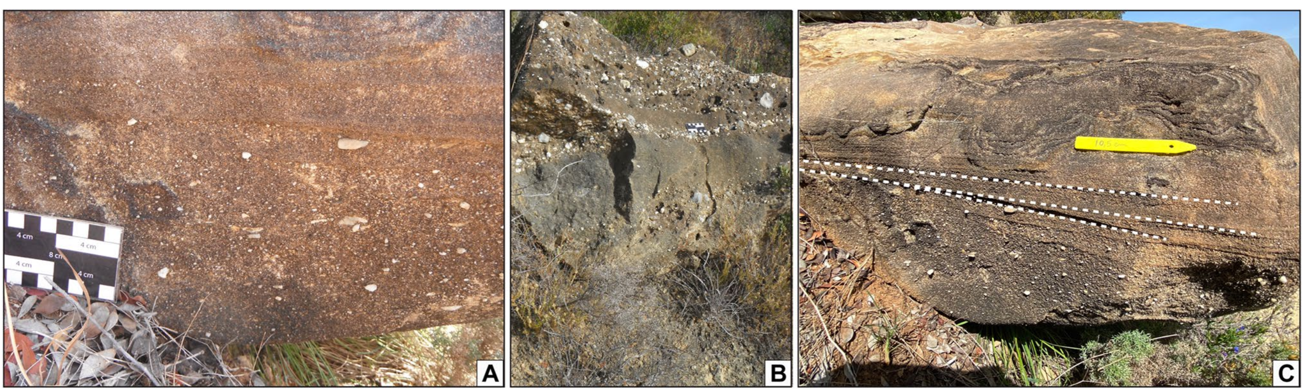

Fig. 15 *Jordana* formation. In some places, the layers have a superficial dark color, due to present-day lichens. Sediment particles with positive gradation (**A**); conglomeratic level in the *Jordana* Formation (**B**); cross-stratification (evidenced by dashed white lines) and "elephant skin" type microbial structures (**C**). Photos © Oliveira and Moura

Pangea supercontinent during the Mesozoic Era formed two new continents, Laurasia and Gondwana (Fig. 19), separated by the Tethys Ocean, which later originated the Mediterranean and the Central Atlantic Ocean. The vertical variation in rock type and fossil content (Fig. 8) of the *Escarpão* Plateau sequence is due to the diverse subenvironments in which sediments were deposited (see text above), resulting from the combination of two processes: sea level change, with a mean sea level higher that today during the Jurassic, and landmass vertical movement, corresponding to a continental uplift.

Site 5—the Water That Feeds Aquifers: Fields of Sinks

The *Escarpão* Plateau is the main recharge zone of the *Albufeira-Quarteira* rivulet aquifer; hence, any activity taking place on the surface has repercussions on the water quality of this important aquifer (Monteiro et al. 2007). This geodiversity site, corresponding to a field of water sinks, illustrates well the karstic processes that produce an underground network of conduits and caves at variable depths, in which the water easily reaches the groundwater table

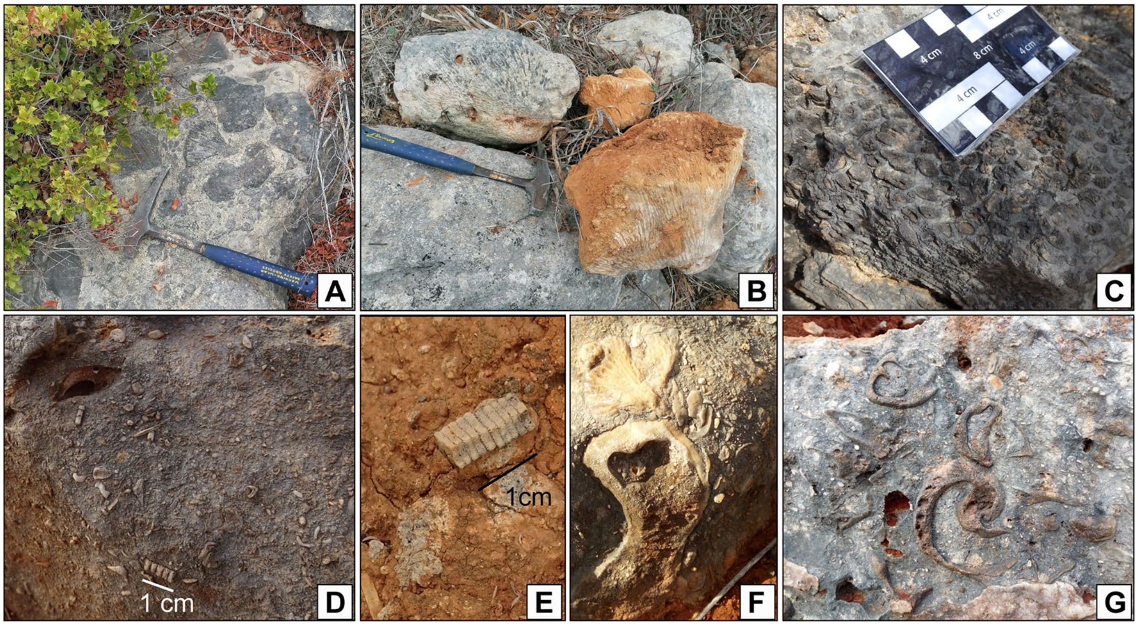

Fig. 16 Fossils of organisms that lived on the continental shelf of the Jurassic Ocean: corals (**A**–**C**), crinoids (**D**–**F**) and rudists (**G**). Photos © Moura and Oliveira (2022)

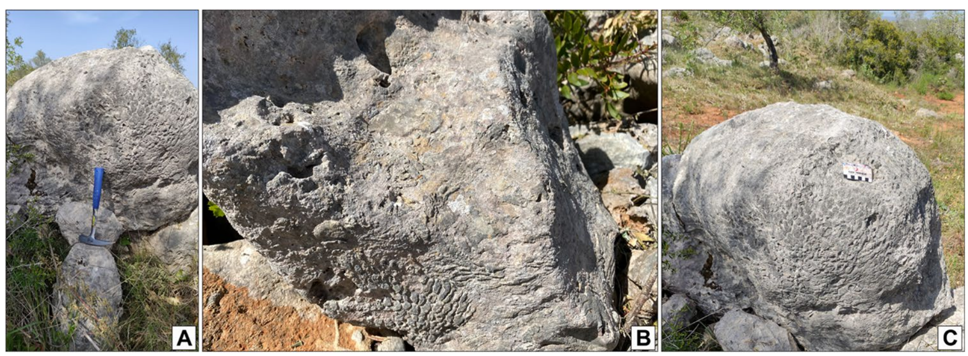

Fig. 17 Blocks resulting from coral reef fragmentation (**A**–**C**). Photos © Moura and Oliveira (2022)

through dolines and sinkholes directly in contact with the atmosphere (Fig. 20).

At this site, rocks include fossils of marine organisms and structures composed of roughly spherical particles, called ooliths and pisoliths (Fig. 21), providing complementary clues to the depositional environment, since these structures were formed in warm coastal areas.

Site 6—Escarpão Plateau Biosite

On top of the *Escarpão* plateau, there is a remarkable floristic and faunistic biodiversity, benefitting from the geological diversity and mosaic of habitats, including rocky outcrops, scrubland in an excellent state of preservation, and carob forests. Endemic plants and several other species that are rare in Portugal can be found here (Fig. 22), such as the foxglove, the *Lusitanian serratula*, the *Barrocal* blue hyacinth and the *Barrocal* laurel, in the shrubby clearings. The predominant crop in dryland orchards is the carob tree, a Mediterranean tree grown throughout the Algarve (Fig. 22). This flora type is characteristic of *terra rossa* soils, the typical soil of limestone weathering in Mediterranean climates, which are very thin, poor in organic matter and mainly composed of iron-rich minerals and clays.

In the mosaic of scrubland and dryland orchards, the fauna is also an important element allowing the observation of birds, mammals, or insects (Fig. 23), as well as reptiles such as the bush lizard and several species of snakes, close to rocky outcrops and in the valley.

Site 7—the Escarpão's Karst

This geodiversity site allows for the discovery of epikarst landscapes derived from the dissolution of carbonated

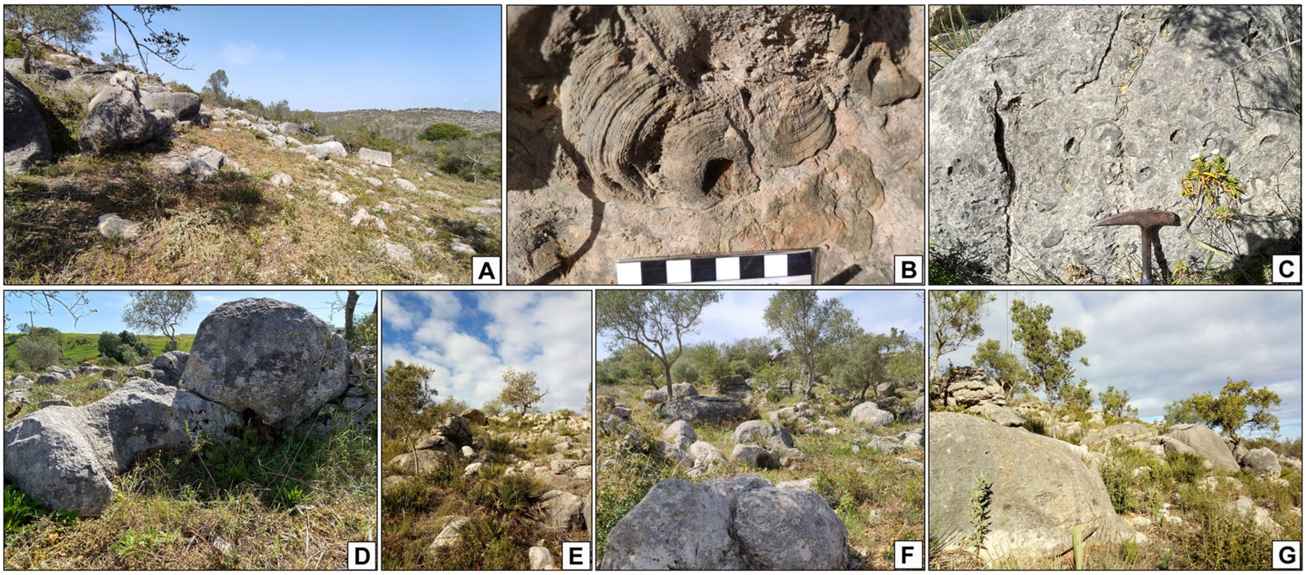

Fig. 18 Chaos of blocks (**A**); block with stromatoporoid fossils (**B**); block with fossils of rudists (bivalves) (**C**); lapiaz field (**D**–**G**). Photos © Moura and Oliveira (2022)

landscapes and contain a remarkable diversity of forms, such as lapiaz, sinkholes, and dolines (Fig. 4).

The karst development starts at the surface with the dissolution of the rock, favored by discontinuities (Fig. 24) as in the limestones of the *Escarpão* and *Cerro da Cabeça* Formations that are very vulnerable to dissolution by rainwater (Figs. 4 and 24). The rocks' alteration continues over time, creating a chaos of blocks (*Barrocal*) on the land surface, with some blocks standing out due to their dimensions, forming fields of lapiaz (Fig. 4).

The persistent work of several generations that removed stones from the soil managed to transform some karstic plains forming flats (morphological term for flat zones) into productive soils for cereals. There are still some indicators of the importance that cereal production played in the traditional economy such as the number of mills now abandoned (for example, the *São Vicente, Cotovio* and *Malhão* mills) in the peripheral region of the *Escarpão* Plateau, or the number of magnificent drystone walls that were built with the stones removed from the lands for agriculture purposes. These walls were meant not only to separate properties but also to support the soil without creating ecological barriers (Fig. 7).

Site 8—Alluvium of the Quarteira Rivulet

This geodiversity site allows us to better understand the seasonal, natural fluvial systems of the *Quarteira* rivulet and its tributaries, *Algibre* and *Alte* rivulets, which are characteristic of karstic and Mediterranean regions. During the rainy season, if the rains are intense, they flow in torrents, rapidly reducing to a rosary of small puddles when the precipitation ceases (Fig. 25). The water seeps into the substrate through sinkholes (Fig. 20) to feed the aquifers. Over the years, floods deposit fine sediments on the rivulets' margins, giving rise to alluvial zones or floodplains that constitute fertile soils, often among the few soils suitable for agriculture in these karstic regions (Fig. 6). However, these alluvial margins are rare along the *Quarteira* rivulet segment that crosses the *Escarpão* Plateau. There, the rivulet banks are abrupt due to their vigorous embedding into the Plateau, exposing visible rocky outcrops (Fig. 26).

Site 9—Quarteira Rivulet Biosite

The *Quarteira* rivulet biodiversity site is in a shady area along the abrupt banks of the rivulet (Fig. 26) and is occasionally flooded, thus having a contrasted humid environment compared with the biodiversity site 6. The presence of oleander and tamarisk along the riverbed, two shrubs with flexible branches that resist to the force of the rivulet's seasonal floods (Fig. 27), is characteristic of this riparian vegetation, whereas the ash is the most abundant tree species on the banks and floodplains. Some herbaceous plants such as fescue, embude, and mentaster are also common on the rivulet banks, as are various species of cyperaceous plants such as bunho, triangle, and bulrush (Fig. 27). Noteworthy is the fact that this segment of *Quarteira* rivulet is the only known habitat of the *Barrocal* reed, a bulbous Algarve endemic plant seriously threatened with extinction. Faunal diversity also benefits from the riverine environment conditions where birds, mammals (otter), reptiles (pond snake),

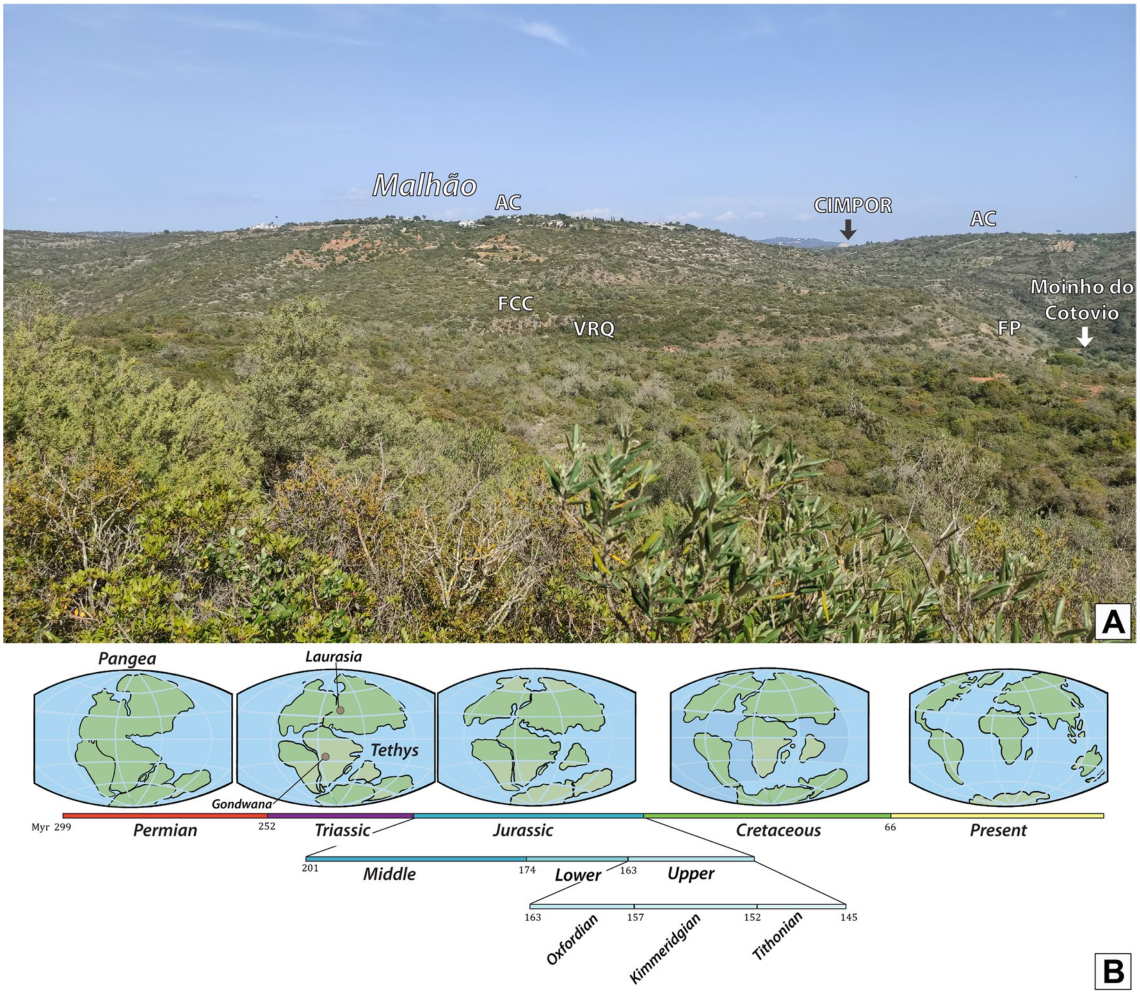

Fig. 19 View of the *Escarpão* Landscape site with Karst flattening (AC), the *Cerro da Cabeça* Formation (FCC), the incision of *Quarteira* Rivulet valley (VRQ), the *Peral* Formation (FP), the CIMPOR limestone quarry of the *Escarpão* Formation and dolomites of *Santa Bárbara de Nexe* (ca. 165 - 145 million years old) and the *Moinho do Cotovio* water mill; Evolution of landmasses along the Paleozoic (Permian) and Mesozoic Eras (Triassic, Jurassic and Cretaceous) (**B**). After Moura and Oliveira (2022)

and amphibians (tree frog) find their necessary resources (Fig. 28). Finally, the diversity of dragonflies stands out among the invertebrates, with several species already previously presented in the Biodiversity Station of *Quarteira* rivulet.

Site 10—Terraces of the Quarteira Rivulet

This geosite provides a 250-m-long outcrop of ancient alluvium representing fluvial terraces settled between 5 and 10 m above the present riverbed (Figs. 5 and 29). They are composed of pebbles and cobbles of graywacke, schist and quartzite (Figs. 5 and 29), originating from the Paleozoic rocks of the northern *Serra* sub-region (Fig. 2). It is likely that these terraces are related to the rapid vertical embedding of the *Quarteira* Rivulet bed, which occurred in response to the lowering of the sea level during the Last Glacial Maximum (18,000 years ago), when the mean sea level was between 120 and 140 m below the present one.

Site 11—the Floodplains—Water Use

Geodiversity site 11, a local cultural landscape, aims to present the straightforward relationship between geomorphology and human land use since the floodplains are naturally fertile soils close to a water body. Although floodplains currently support small orchard of carob trees (Fig. 22), the presence of ancient irrigation systems such as *levadas* (elevated channels) and weirs (Fig. 6) reveals their agricultural importance in the past (Fig. 30).

The *Moinho do Cotovio* water mill (Fig. 19) is a good example of how fluvial dynamics varied over time, depending not only on natural changes in the rainfall regime but also on man-made alterations in the riverbed. It is nowadays

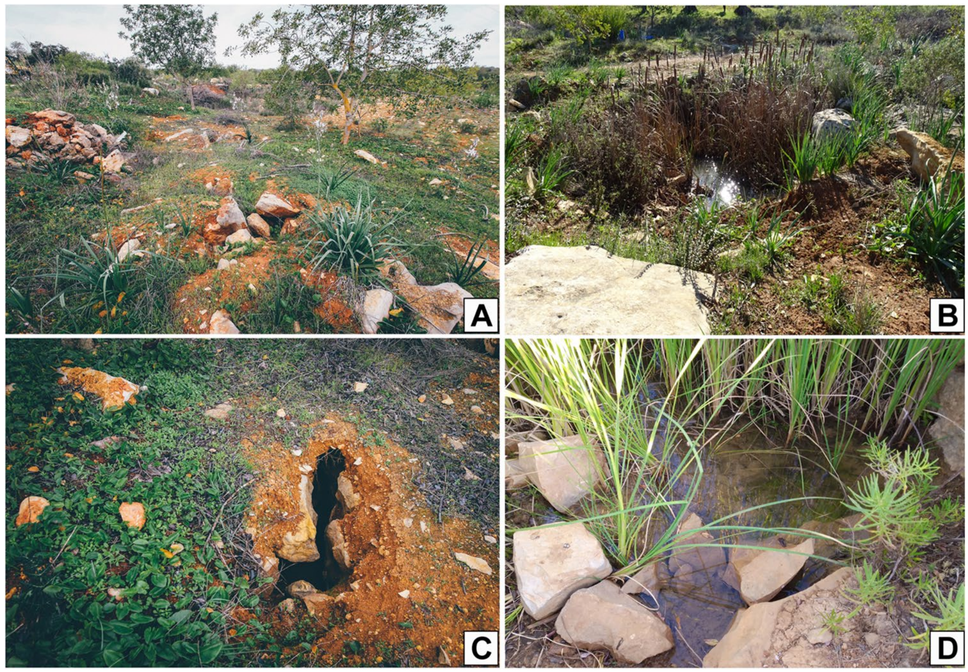

Fig. 20 Aspects of the sinkholes at the site: General view of the geodiversity site (**A**); stream Sinks (**B**–**D**). Note the vegetation that is completely distinct from other vegetation on the Plateau. Photos © Gregório, Pereira and Oliveira

Fig. 21 Photographs of oncolith specimens: ooliths (**A**, **B**) and pisoliths (**C**). Photos © Pereira and Oliveira

difficult to visualize how the mill was running using the rivulet water flow since the riverbed is almost always dry (Fig. 30). The water was directed from the downstream meander weir through a *levada* to the mill structure to propel the two millstone sets of this roller mill (Fig. 31). This structure is rectangular and built in *taipa* (rammed earth) masonry with a one-flap roof (destroyed). It probably had an inner structure composed of wooden beams, reeds, and old Portuguese tile. Based on information from other mills in the area, we assume that the structure dates from the second half of the 18th century (mentioned in a municipal document 1779) and that it would have functioned until the 1940s.

Public Engagement

The importance of the *Escarpão* Plateau in terms of geoheritage has been validated and recognized by the scientific community (Manuppella 1992; Ramalho 2015; Terrinha et al. 2006) and the technical team of Algarvensis aUGGp (Moura and Oliveira 2022; Oliveira et al. 2021a, 2021b) as being the only site in the eastern Algarve where a complete sequence of sediments accumulated in the Tethys Ocean during the Upper Jurassic (163.5 to 145.5 million years) can be observed (Figs. 2 and 3).

However, neither the community nor the various public entities, from local to regional influence, have acknowledged the importance of the *Escarpão* plateau or its relevance in terms of biodiversity and geodiversity as a natural heritage to preserve.

This might be due to fact that although the *Escarpão* Plateau represents a site of great geoheritage value and scientific interest, it also became, over the last decades, a site with several environmental issues: active quarries, a sanitary landfill with leachate run-off problems, and an active waste transfer center. This latter gives generates a lot of rubbish and garbage accumulation along the access routes, which gives the site a degraded and dusty appearance.

Fig. 22 Landscape aspect with Mosaic of scrubland, rocky outcrops, and carob trees (**A**); aspect of a dryland orchard (*alfarrobal*) with *Terra Rossa* soil (**B**). Photos © Carapeto

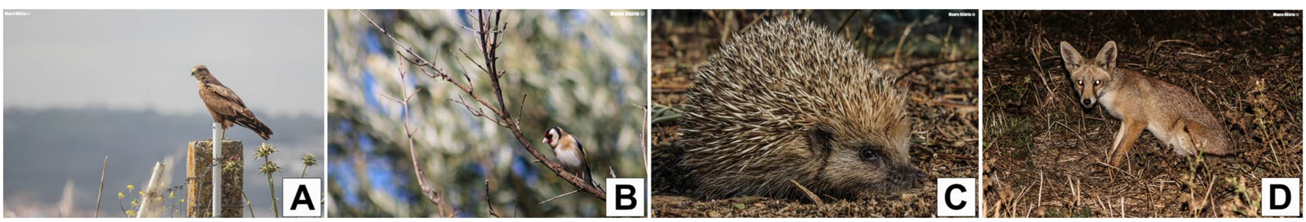

Fig. 23 Some birds and mammals that can be observed: buffy tuft (**A**), goldfinch (**B**), hedgehog (**C**), and fox (**D**). Photos © Hilário

As means to counteract this situation, three different approaches were designed:

- Outreach: Outlining a proposal for visiting the geosite, based on a storytelling presentation of the different sites of geological and biological interest, that would help visitors understand the natural heritage and at the same time enjoy a pleasant moment at the site with the walking route.
- Stakeholders: Looking at the quarry and their activities as an integral part of the *Escarpão* geosite, and thus developing connections with stakeholders to make them aware of the geopark project and to invite them for a partnership work, integrating activities, creating synergies to visually improve the space and to create visitable areas and interest points inside the quarry.
- Societal Commitment: Engaging the local community and local public entities to educate on the value and the need of protecting the geological heritage and natural environment.

Hence, several resources for outreach and public awareness were conceived based on the scientific information published as a science communication book in Portuguese entitled "A many millions of years old story - from the Tethys Ocean to the Barrocal region of Algarve" written by Moura and Oliveira (2022), in which more than 28 sites of geoheritage or geodiversity interest are identified and inventoried. From these, 11 sites (Table 1) have been chosen to conceive a new pedestrian route and to build a storymap "A Dive into the Jurassic Sea" that links the storytelling to the map visualization (Oliveira et al. 2021a).

Meanwhile, a geoeducation program directed to the educational community has also been developed proposing visits and field trips for teachers and students to the *Escarpão* plateau. This program allows complementing the school syllabus and creating a greater sense of belonging since it connects the school community to the Geosite, which becomes a study case for several schoolworks.

Regarding the societal and stakeholders' commitment, the contacts and information made by the Algarvensis

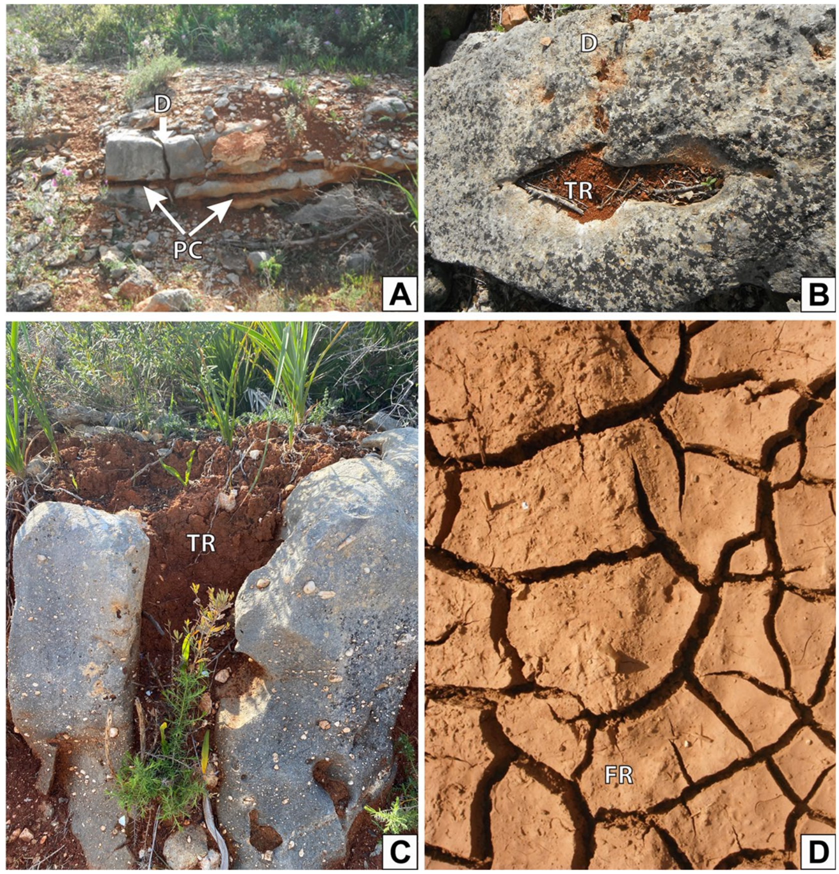

Fig. 24 *Terra Rossa* (TR), an insoluble, reddish-colored residual product of limestones dissolution. *Terra Rossa* along the planes between layers (PC) and the fractures or diaclases (D) in which the infiltration of water is facilitated and therefore the dissolution of the rock (**A**, **B**). *Terra Rossa* (TR) constitutes most soils in karst areas (**C**). *Terra Rossa* is mainly composed of clay, which makes the soils difficult to work, because they become flooded during rainy periods and dry out during dry periods, opening retraction cracks, or mudcracks (FR) (**D**). Photos © Moura and Oliveira (2022)

Fig. 25 Examples of local rivulets' hydrodynamic. *Quarteira* Rivulet, looking upstream from the Purgatório bridge, only 6 days apart, respectively, on December 20th, 2020, after intense rainfall (**A**) and on December 26th, 2020 (**B**); under the *Purgatório* bridge the rivulet bed was completely dry on both days (**C**). *Algibre* Rivulet, looking upstream from the *Purgatório* bridge, only 6 days apart only 6 days apart, respectively, on December 20th, 2020, after intense rainfall (**D**) and on December 26th, 2020, when only a few ponds remained (**E**). Photos © Moura and Oliveira (2022)

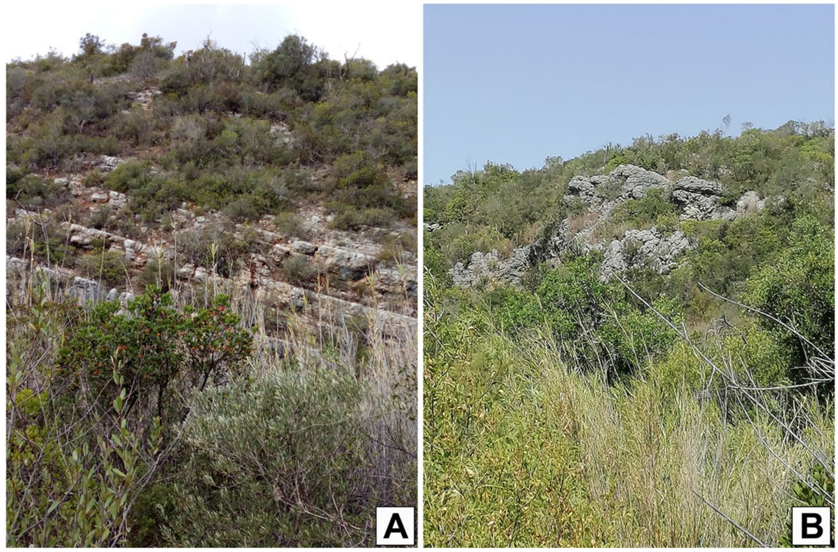

Fig. 26 Abrupt banks of the *Quarteira* Rivulet crossing the *Escarpão* Plateau, where the limestone layers can be seen (**A**, **B**). Photos © Moura and Oliveira (2022)

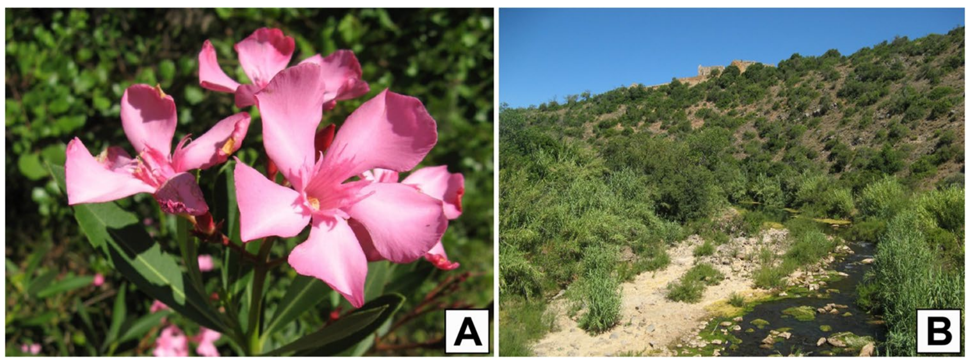

Fig. 27 Flowering of the oleander which is an attraction at the beginning of summer (**A**). View of the valley of *Quarteira* rivulet, upstream from the Castle Bridge (**B**). Photos © Pereira and Oliveira

Fig. 28 Examples of reptiles and amphibians from the riparian environment**:** Mediterranean terrapin (**A**), Mediterranean greenfinch (**B**), Mediterranean pond snake (**C**), Mediterranean tree frog (**D**). Photos © Hilário and Planeta Água - Ciência Viva

aUGGp team allowed raising awareness for the value of the geoheritage and its conservation. The owners of the quarry, instilled with a sense of social responsibility, began clearing debris from the quarry, so that along the access routes the visual environment would be more welcoming. In parallel, the bituminous production industry plant autochthonous trees that allow a more natural appearance to the surrounding area.

The new walking route also sustains interpreted visits to the *Escarpão* Plateau presenting the geological formations of the Oxfordian and Kimmeridgian, but also the unique floristic values that have also been identified, such as the *Narcissus willkommii* (Sampaio). This led to the first step of a safeguard plan co-development with the local community based on a citizen science project.

And from a touristic point of view, we counted about 1000 visitors since the hiking trail PR4 ABF was signposted in September 2021, some of whom answered a survey on their interest in the geological information along the route as well as on their potential total expenditure in the territory.

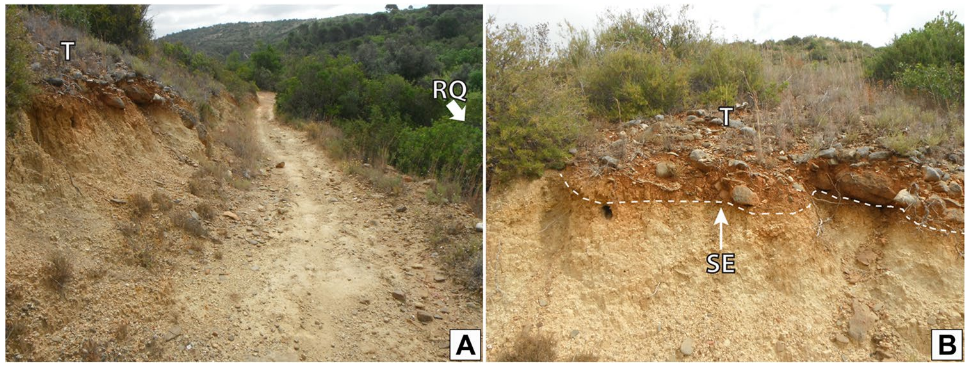

Fig. 29 Photographs of the fluvial terrace. Topographic relationship between the *Quarteira* Rivulet terrace (T) and the rivulet present-day bed (RQ) (**A**); erosive surface (SE) between the terrace and the substrate on which it is deposited (**B**). Photos © Moura and Oliveira (2022)

Fig. 30 Spatial relationship between the Quarteira Rivulet bed (LRQ), the terrace (T) and the alluvium (A) (**A**); *Quarteira* Rivulet sections near *Moinho do Cotovio* (**B**, **C**). Note the blocks in the rivulet bed, resulting from the erosion of the limestones on the banks; pebbles from the old rivulet bed (**D**-**E**). Photos © Moura and Oliveira (2022)

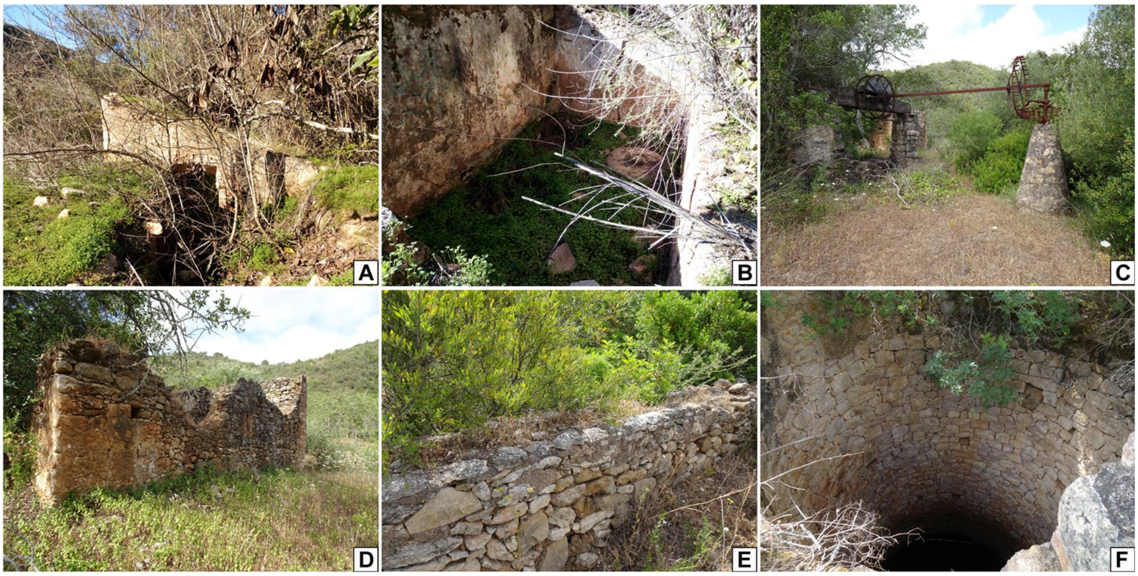

Fig. 31 Examples of water use structures from the area: abandoned watermill *Moinho do Cotovio* (**A**, **B**); *nora* (**C**); warehouse (**D**); *levada* -elevated channel (**E**); well (**F**). Photos © Pereira, Oliveira, and Moura

Fig. 32 Events of *Geopalcos* in 2021: artistic installation on *Paderne* Bridge over *Quarteira* rivulet from Vanessa Barragão (**A**); poetry paths along the rivulet (**B**); concert in the *Paderne* castle with João Frade & Aenigmaticus orchestra (**C**)

The first results give an average of 10 euros per walker spent in local market (unpublished data).

Finally, the *Escarpão* geosite and the cultural and monumental heritage in its vicinity received several artistic events (concert, installation, poetry paths; Fig. 32) during the first edition of the biennial event called Geopalcos - Art, Science and Nature. The primary aim for creating this event was to place the geosites of the Algarvensis aUGGp territory in the center of attention with cultural activities for the public, connecting the themes of art, science, and nature, and leading the nature lover to discover the geosites through a cultural proposal (Martins et al. 2021).

Final Remarks

This is the first project completely developed under the umbrella of the Algarvensis aspiring UNESCO Global Geopark, which is still at an early stage of development. Nevertheless, the *Escarpão* Plateau project is a successful initiative that managed to deliver outcomes in all the priority axis of intervention, such as:

- Science, Geoconservation, and Environment: New scientific information has been produced, and an initial plan for geoheritage conservation has been drafted in collaboration with local and regional public and private entities.
- Education: Field guides and interpreted visits to the Escarpão Plateau landscape geosite and its nested sites have been created and promoted.
- Culture: Several artistic events have been shaped and implemented.
- Tourism: New geotouristic products, including the PR4 walking trail, have been developed and delivered.
- Communication: The outreach information has been incorporated into several digital platforms such as ESRI storymap and iHeritage application, besides the webpage of the Algarvensis aUGGp.

All these outcomes have allowed the project to influence opinions and create awareness of the Escarpão Plateau's natural heritage. Students from the Master's in Landscape Architecture at the University of Algarve have started developing several proposals for new routes (cultural geopaths) and landscape interventions for the *Escarpão* plateau geosite.

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Declarations

Conflict of Interest The authors declare no competing interests.

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