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Geoconservation in the Cabeço da Ladeira Paleontological Site (Serras de Aire e Candeeiros Nature Park, Portugal): Exquisite Preservation of Animals and Their Behavioral Activities in a Middle Jurassic Carbonate Tidal Flat

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Abstract: The Cabeço da Ladeira paleontological site in central Portugal became known as the "Jurassic Beach". Formerly an active quarry, the site was protected in order to preserve the large exposures of a Middle Jurassic (early? Bajocian) carbonate tidal flat with an outstanding fossil record. This multidisciplinary paleontological work involving experts from several national and international research and geoconservation institutions was carried out under the umbrella of the Institute for Nature Conservation (ICNF), since this geosite is located within the Serras de Aire e Candeeiros nature park. Cabeço da Ladeira has provided exquisitely preserved body fossils, especially echinoderms, together with the exceptional preservation of their, and other, animal's behaviors. It is also a hotspot to understand the diversity of bivalves in the Middle Jurassic. Due to the large area of the geosite, the international relevance of the findings, and the risk of weathering and destruction of the fossils, a geoconservation plan has been developed by ICNF with the support of local authorities. After several years of being open to visitors without proper control, the Cabeço da Ladeira paleontological site is now conditioned to organized groups of researchers, schools, and tourists. Some body fossils were collected for studies and included in the national collections of the Geological Museum (Lisbon). Moreover, casts have been made to protect holotypes of trace fossils, also providing ways to replicate this fossil record in temporary exhibitions. A long-term experimental study to conserve the limestone bedding plane exposures and their fossil contents was started in order to develop the best geoconservation strategy with an aim to reduce the damage produced by the increasing tourist demand on natural sites. Cabeço da Ladeira and other geosites in protected

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areas are key to communicating an evolutionary approach to environmental education, and their geoconservation must be a priority to improve their long-term use as (geo)tourism attractions.

Keywords: "Jurassic Beach"; echinoderms; bivalves; trace fossils; carbonate tidal flat; geoconservation measures; geotourism; nature park; central Portugal

1. Introduction

Body fossils (the remains of the body parts of ancient life) and trace fossils (activities of ancient organisms preserved in a substrate) represent major evidence for reconstructing ancient ecosystems. However, conditions leading to the preservation of trace fossils are remarkably different from those of body fossils [1]. As a result of this differential preservation, trace fossils are commonly preserved in rock units that are otherwise unfossiliferous, whereas the possibility of relating a trace with its tracemaker is precluded by the inherent nature of the fossil record [1–3]. Therefore, finding a trace fossil associated with its maker is rare and worthy of special attention. These general rules are defined by the Cabeço da Ladeira Paleontological Site (Portugal), known since 2003 for its exceptionally preserved fossil echinoderms [4,5] and, more recently, for its extensive trace fossil record [6]. These exceptional features, together with growing evidence for a diverse biota, make this former active quarry a geosite with international relevance [7].

The fossil association of the Cabeço da Ladeira paleontological site can only be truly grasped by the general public via its interpretation in situ. With the discovery of the first fossils, it was established by the responsible authorities that the geoconservation strategy of this heritage was to be carried out on-site. Several of the most significant invertebrate and vertebrate trackways and trails occupy extensive areas, which are almost impossible to safely remove, and, through that, the sense of context would also be lost for both body and trace fossils. Since then, several steps were taken to preserve and study these fossils, while the site was protected. We hereby describe in detail the approach taken to the preservation and conservation of both fossils and the site. Some representative body fossils were retrieved for the national collections of the Geological Museum in Lisbon, for study and safe keeping. However, thousands of body and trace fossils were already inventoried and left in place or replicated, waiting for proper conservation measures. To our knowledge, this is the only site in the world where visitors can observe fossil echinoderms in situ where their preservation is going to be attempted on site.

2. Discovery and Legal Protection of the Cabeço da Ladeira Paleontological Site

In 2003, during an inspection visit to the Cabeço da Ladeira quarry—then in operation—technicians from the natural protected area known as "Serras de Aire e de Candeeiros" Natural Park (PNSAC) where the quarry is located found exceptionally preserved echinoderm fossil remains. Since then, the site has been closely monitored. Two years later, a team from the Geological Museum of the National Energy and Geology Laboratory (LNEG) (the former Geological Survey of Portugal) and the Universidade Aberta attested the scientific importance and rarity of those fossils and made the first casts from several specimens. A few of the specimens from which the casts were made were later stolen. In the following year, the paleontological relevance of the findings was informally confirmed by Andrew Smith (who was, at the time, curator of the Natural History Museum, London, United Kingdom) as a world reference in the study of fossil echinoderms.

The Cabeço da Ladeira paleontological site was formally protected in 2010, under national legislation. The new PNSAC's Management Plan considered it to be a "site of special geological and paleontological interest, whose conservation of the values in it was necessary to be carried out". Within the scope of this document, the Institute for Nature Conservation and Forests (ICNF)—the authority responsible in Portugal for the management of the protected areas—in cooperation with the LNEG, the Municipality of

Porto de Mós where the Cabeço da Ladeira site is located, as well as researchers linked to universities and other scientific and geological heritage conservation organizations have been developing actions to study and safeguard the paleontological site. The quarrying activity was formally ended in May 2013, followed by a mandatory landscape restoration plan. In this particular case, the plan consisted of cleaning the extensive limestone bedding planes from debris, for prospecting new fossils and stabilizing rubble piles developed during the quarrying activity. These required interventions resulted in the discovery of thousands of echinoderms and other animal body fossils and trace fossils, some of which are exceptionally well-preserved.

3. Geological Setting

The Cabeço da Ladeira geosite is located about 2 km to the north of the village of São Bento, the municipality of Porto de Mós (central Portugal), in the Santo António Plateau. This area lies within a morphostructural unit called 'Maciço Calcário Estremenho' (MCE), a Jurassic limestone massif in the Lusitanian Basin uplifted by the Alpine compressive tectonics [8] (Figure 1).

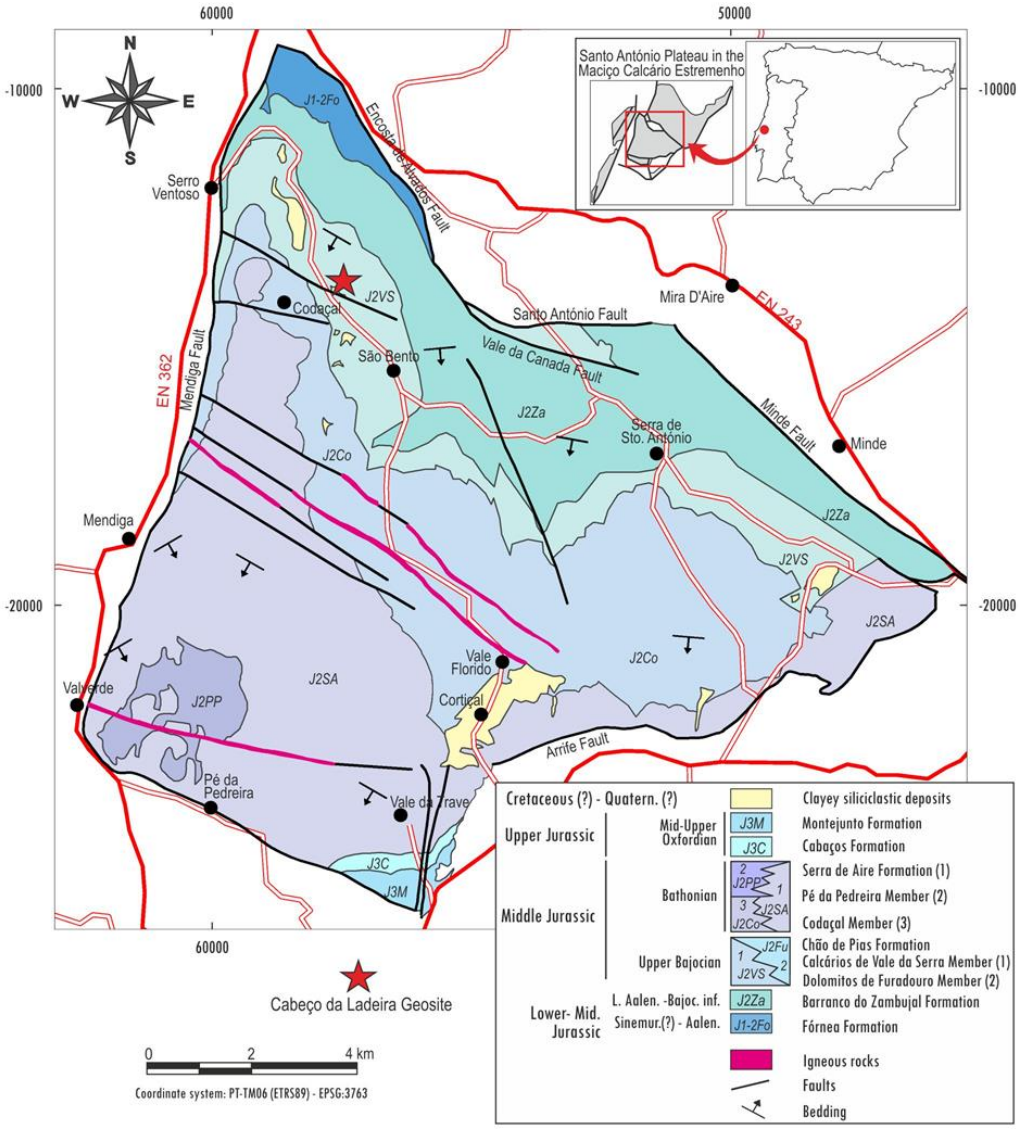

Figure 1. Geological setting of the Cabeço da Ladeira paleontological site (adapted from the Geological Map of Portugal, sheets 26-B, 26-D, 27-A, and 27-C, scale 1:50,000, edited by LNEG). Lithostratigraphy from [8,9].

MCE is partially included in the area of PNSAC, which is the most important protected area for karst geomorphology in Portugal [10,11]. It bears many natural caves and large poljes among a great diversity of karstic structures and landforms, as well as dinosaur tracksites of Middle Jurassic age as the most relevant geological heritage [11,12]. The PNSAC is considered an important region for understanding the geological evolution of the Lusitanian Basin related with the opening of the North Atlantic during the Mesozoic, and it is the best place to study Middle Jurassic shallow-water depositional systems in Portugal [13].

Since the works of numerous authors [8,14–16], among others, and a more recent compilation of [9], the lithostratigraphy of the MCE is well known. Particularly for the Santo António Plateau, where the geosite is located, most of the exposed rocks are limestones and argillaceous limestones formed in a carbonate ramp depositional system of Middle Jurassic age.

According to Azerêdo and Kullberg et al. [8,9], the stratigraphic sequence in the Santo António Plateau begins with the Fórnea Formation, mostly of Lower Jurassic age, comprising brown and grey marls and argillaceous limestones outcropping in a small area of the plateau. Their deposition has occurred in a gently dipping carbonate ramp environment. Overlying this unit occurs a rhythmic sequence also composed of marls and clayey limestones that correspond to the Barranco do Zambujal Formation (lower Aalenian-to-lower Bajocian). In the upper levels of this formation, the clayey component diminishes progressively, and the fossil content indicates an external ramp marine environment. This sequence is followed by the Chão das Pias Formation (lower (?)-upper Bajocian), which in the Santo António Plateau is represented by the Calcários de Vale da Serra member, which has a thickness of 50 m–60 m. The fauna of the Cabeço da Ladeira geosite occurs in the upper levels of this member, which comprises slightly argillaceous micritic and biomicritic limestones (mudstones and wackestones). To the top, these gradually turn to calciclastic limestones (intrapelmicrite and biopelmicrite wackestones–packstones), and the top levels correspond to packstones and grainstones. The basal section of this member shows that the deposition still took place in an open marine environment, but gradually became less deep, regressing with shallow facies prograding from East to West. From the beginning of the Bathonian, facies of a shallow and very dynamic environment were deposited. They show complex lateral and vertical variations and are represented by the Santo António–Candeeiros Formation (Codaçal, Pé da Pedreira, and Moleanos members) and the Serra de Aire Formation. The Santo António–Candeeiros Formation comprises massive bodies of grainstones and rudstones typical of an oolitic barrier environment. The Serra de Aire Formation corresponds to a thick sequence of micritic limestones, with the basal levels representing peritidal environments, and the upper levels typical of ante-barrier lagoons.

Bedding in the Santo António Plateau dips slightly to the south—up to 10°—but near major faults, it is strongly tilted as an effect of the reverse movement of those same faults. This is particularly the case for the strata next to the Arrife fault that limits the plateau to the southeast, and next to the Vale da Canada and Santo António faults, immediately north of the Serra de Santo António village. The general structure of the Santo António Plateau is still marked by some NW-SE faults that locally are intruded by dolerites.

4. Materials and Methods

From the upper part of the Chão das Pias Formation, a sequence of seven beds is widely exposed in an area over 3300 m^2 (Figure 2). This geosite was a former quarry, where limestones were extracted for the construction of dry-stone walls, typical in the area, and pavements. The site was mostly covered with piles of rejected stone, hiding most of the fossiliferous limestone beds.

With the intention of definitively stopping the quarrying activity, an Environmental Recovery Plan was devised, as is mandatory under Portuguese law. With this intent and with the prior preliminary recognition of the importance of the fossil record, as previously

mentioned, this plan had to consider the safeguard and preservation of the site and its fossils.

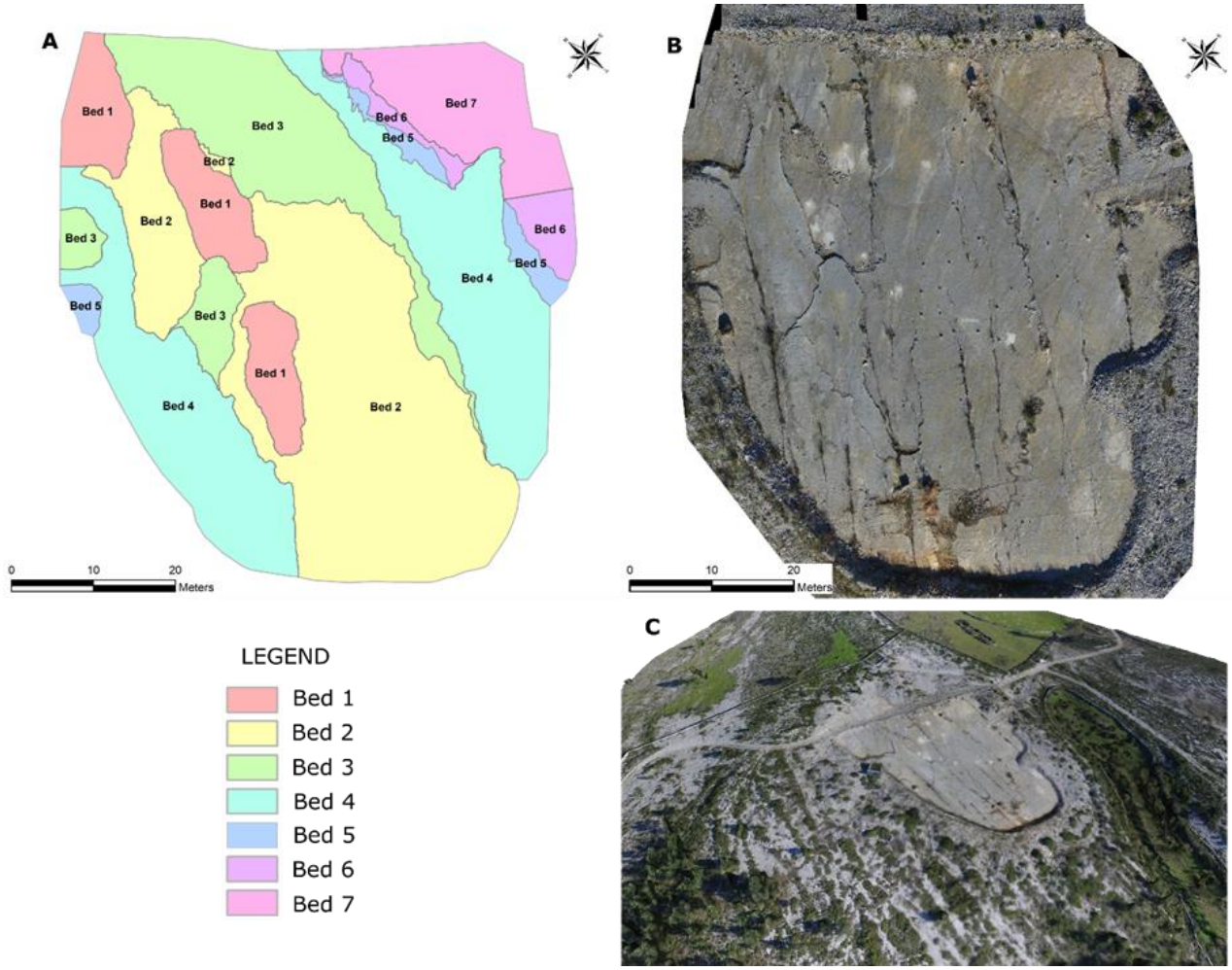

Figure 2. Vertical and oblique views of the former quarry of Cabeço da Ladeira. (**A**) Mapping of the seven different beds identified on the studied geosite, (**B**) orthophoto of the geosite for comparison, and (**C**) oblique view of the textured 3D model of the geosite and the main accesses after the Environmental Recovery Plan.

This plan created conditions for the full understanding of the total number and relevance of the fossils in their present setting, the preservational requirements of the fossil record and sedimentary structures in the stratigraphic context, as well as the potential use of the site for geotourism. With that intent, the Environmental Recovery Plan consisted in practical terms of removing all of the rubble piles present over the bedding plane exposures toward the quarry limits and seeding the surrounding area with indigenous vegetation.

Most of the rubble was moved to the former quarry limits, using an excavator with rubber wheels. The rubber wheels were essential to minimize the impact of the cleaning intervention over the outcropping rocks, since there was no indication where the fossils were, and the excavator needed to operate on the fossiliferous bedding plane exposures. This action allowed for the removal of most of the loose rocks. This step was decided upon in order to maximize the exposed area during quarrying, allowing the paleontological works to be developed.

The next component of the plan was to naturalize the surrounding area through the plantation of indigenous vegetation. These plants stabilized the rubble piles formed at the site limits, and nowadays confer a more natural aspect to the surroundings.

After the Environmental Recovery Plan was completed, the next step was to fully understand the fossil record present on those extensive bedding surfaces. For that, the outcropping beds were carefully cleaned by hand with brooms and water by the scientists, with the help of the natural park technicians, many volunteers, and local fire fighters. The result was a clean exposed set of seven beds that can be seen today (Figure 2).

During the last ten years, a great amount of work has been carried out both in the field and in the office with the systematic inventory of the geological/paleontological heritage as part of a broader geoconservation process in the PNSAC. During these years, a technical-scientific working group was consolidated for the Cabeço da Ladeira geosite. This working group included several experts from different Portuguese research institutions of various areas related to the geosciences and geoheritage, with the coordination of LNEG for the scientific area and the ICNF for geoconservation, along with the support of both the Municipality of Porto de Mós (CMPM) and the Council of São Bento (JFSB).

A 1 m squared-grid was defined in a total area of 2975 m^2, and the fossil content for each square was carefully recorded and photographed. From this systematic work, dozens of articulate and semiarticulate exquisitely preserved echinoderm specimens were found. Also of relevance is the fact that many different trace fossils from different producers were recognized [6], many of which are still under study. In some remarkable cases, it was even possible to discover the trace with its maker at the end. Finally, but no less important, is the presence of different types of mollusks, with special mention to the discovery of ammonites, allowing for a constraint of the age of the exposed layers.

From the echinoderms found at the Cabeço da Ladeira geosite, 13 specimens fundamental for taxonomical determination of genera and species were extracted, incorporated in the Geological Museum (LNEG) collections, and replaced by replicas in situ. Several trace fossils and some body fossils were casted, high-resolution photogrammetric 3D models were developed for selected fossils, and a detailed GIS model of the paleontological site was obtained from georeferencing hundreds of fossils identified by posterior spatial analysis studies.

5. Results

5.1. A Jurassic Site Made of Stars and Their Behaviors

Since late 2015, a systematic paleoecological approach has been developed by a multidisciplinary team. As a result of this team's work, 15 species of echinoderms [4], 15 species of bivalves, 2 species of gastropods, and several still unidentified species of ammonites, serpulid polychaetes, brachiopods, sponges, corals, ostracods, and foraminifers have been identified, as well as 17 ichnospecies attributed to both invertebrate and vertebrate behaviors (partim [6]). Microbial mat-related structures with evidence of subaerial exposure, such as wrinkle structures, Kinneya- and flat-topped ripples, ripple patches, mud chips, and blisters allowed for the determination of Cabeço da Ladeira as a tidal mudflat environment occasionally exposed [6].

In this paleontological site, over 90 articulate and semiarticulate echinoderm specimens were found, among which were echinoids, asteroids, crinoids, and ophiuroids [5] (Figure 3). Almost all the echinoderm fossils found on this site demonstrated exquisite preservation, with all their ossicles still preserved and articulated, as though the animals were still alive. Finding so many well-preserved echinoderms is very uncommon in the fossil record, due to the taphonomic characteristics associated with this animal group. Echinoids are the most abundant of the echinoderms, occurring on all beds bearing echinoderm fossil remains, and are spread around the site. The echinoid fauna is dominated, both in the number of individuals and species richness, by cidaroids (*Heterocidaris solaris* nov. sp., *Paracidaris spinulosa* (Cotteau, 1875), *Rhabdocidaris* sp. A, *Rhabdocidaris* sp. B, *Gymnocidaris* cf. *guerangeri* (Cotteau, 1857), Cidaroida indet. A, and Cidaroida indet. B). Other echinoids are also present, such as *Stomechinus bigranularis* (Lamarck, 1816), *Stomechinus* sp., *Gymnodiadema hessi* (Smith, 2011), and Echinoidea indet. Asteroids are represented by two different morphologies (*Noviaster* sp. nov. and Goniasteridae indet.), also occurring on all

beds where echinoderm remains were found. Articulate crinoids occur on Beds 2 and 7, represented by two different forms (an undetermined isocrinid—a stalked form with cirri and branching arms—and possible comatulids). Finally, two still unidentified ophiuroid specimens were identified on Bed 2.

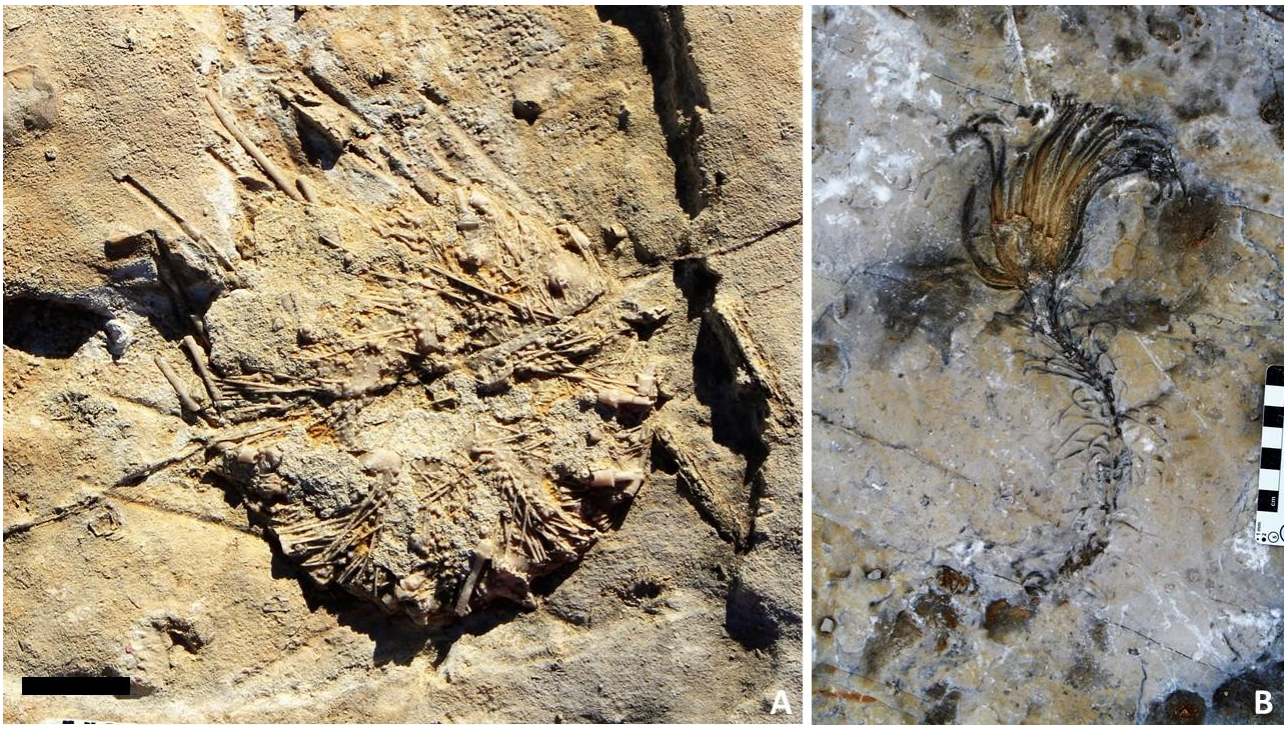

Figure 3. Example of the exceptional preservation of echinoderms at the Cabeço da Ladeira site. (**A**) *Gymnocidaris* cf. *guerangeri* (Cotteau, 1857) with the spines still attached; scale is 1 cm; (**B**) a complete isocrinid crinoid evidencing the fine peduncle cirri; the scale squares are 1 cm in length. Photos taken in the field by the authors.

Of remarkable relevance is the association of trace fossils with their echinoderm makers. Cabeço da Ladeira bedding plane exposures (Beds 2 and 3) exhibit decimeter-to-meter scale trackways composed of sets of numerous bullet-like imprints. One of them shows one *Heterocidaris solaris* nov. sp. preserved at its end, allowing for the attribution of these trackways to a producer in the case of the locomotion of this specific cidaroid. The trackway is 220 cm long and about 15 cm in the widest parts, roughly corresponding to the width of the preserved cidaroid together with the spines. The overall trajectory is almost linear, although the animal may have changed direction in the last moments of its travel before becoming preserved in situ. Neto de Carvalho et al. [6] described the first evidence in the fossil record of a stalked isocrinid autotomy crawling with oral-aboral flexure of the arms after detachment from the substrate, leaving the trail now known as *Krinodromos bentou* (Neto de Carvalho, Pereira, Klompmaker et al., 2016). The fact that the cidaroid presumably intentionally walked together with *Krinodromos bentou* produced by a stalked isocrinid—in the same bed (Bed 2) and a few meters distant from one another—is evidence for predator and prey coexistence. The comprehensive work on echinoderm ichnology of Belaústegui et al. [17] also shows that the cidaroid trackway from Cabeço da Ladeira is the first echinoderm locomotion behavior described from the fossil record.

The presence of articulated individuals associated directly to trace fossils, including the first record of a fossil trail associated to a stalked crinoid [6,17], and trace fossils never described before in the evolutionary stem of clades such as the crabs and the batoids (Figure 4), makes the Cabeço da Ladeira site a unique *lagerstätte* for the Middle Jurassic [4,6,7].

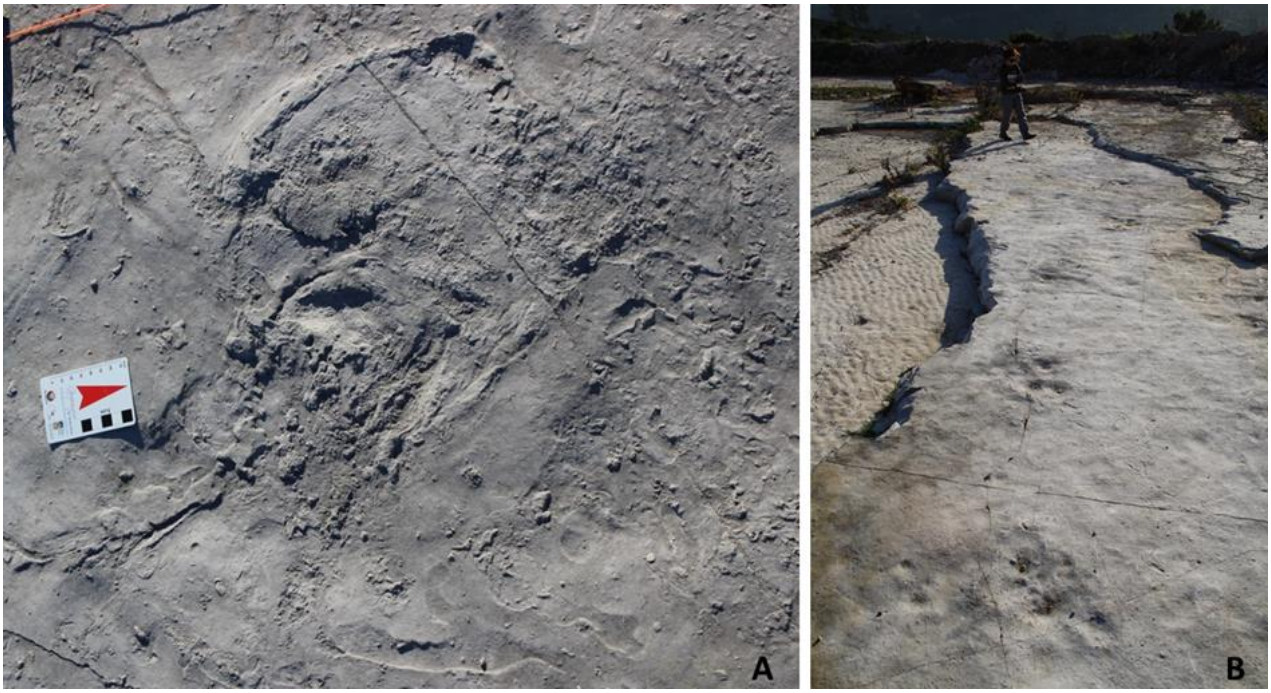

Figure 4. Resting trace of a Rhinobatidae. (**A**) The earliest example of behavior among batoids, where Cabeço da Ladeira shows a high density of feeding pits together with swimming trails, and (**B**) regurgitates attributed to this ancestral clade of the Rajiformes (photos from the authors).

5.2. High Diversity of Bivalve Species and the First Discovered Ammonites

Bivalves are among the marine invertebrate groups with a high potential for fossil preservation, due to their shell's mineralogy and their relative abundance in the biota. Nevertheless, sedimentary facies or the outcropping natural constraints can hinder this assumption. Cabeço da Ladeira is, at the moment, one of the very best fossil sites regarding bivalve records for the Middle Jurassic in the Lusitanian Basin. Although shell preservation is not the best in many cases—a fact related to the tidal flat depositional conditions, weathering by recent exposure and/or with the former quarry activities, and visitor trampling—the fossil record enables us to identify bivalves as a major diverse group at the Cabeço da Ladeira paleontological site. Considering the outcrop conditions and exceptionally large bed surface area exposure, a detailed observation could be carried out where even juvenile specimens were counted. The nearshore facies impose a careful interpretation in terms of paleoecological insights, especially those related to the time-average of the molluscan biocoenoses [18]. Regarding taphonomic condition breakage, shell disarticulation, and fragmentation, epibiont encrustation and abrasion were observed. Nonetheless, articulated specimens (in life-position or in butterfly position) are frequently observed. These simultaneous taphonomic conditions in the assemblages are interpreted as indicative of the discontinuity in the sedimentation process, and a recognizable time-averaging in the assemblages. Considering the postmortem low disarticulation grade of preservation found in several echinoderms (i.e., articulated ossicles and spines), it is reasonable to accept that the time elapsed in time-average was quickly developed, or at least was distinct for bivalves and echinoderms. There is no evident connection between the taphonomic conditions of the shells and the species present. Such absence of evidence could corroborate the interpretation that all the bivalve death assemblages are autochthonous or para-autochthonous and presumed as representative of a live assemblage.

The taxonomic diversity of bivalves is indicated by the record of 15 taxa—with 13 pectinoids, 1 ostreoid, and 1 limoid—which is a considerable degree of diversity considering the restricted ecological association represented (Figure 5). The Bajocian interval was one of the acmes in the bivalve diversity, and the time of the species' first appear-

ance [19,20]. At Cabeço da Ladeira, three species attributed to the genus *Spondylopecten*, namely *S. cardinatus* (Quenstedt, 1858), *S. subspinosus* (Schlotheim, 1820), and *S. palinurus* (d´Orbigny, 1850), were recognized (Figure 5B). Other taxonomical well-represented genera are the pectinids *Pseudopecten barbatus* (Sowerby, 1819), *P. dentatus* (Sowerby, 1827), *Camptonectes* cf. *obscurus* (Sowerby, 1818), *Entolium corneolum* (Young and Bird, 1828) (Figure 5D), *Praechlamys textoria* (Schlotheim, 1820) (Figure 5D), and *Eopecten spondyloides* (Romer, 1836) (Figure 5A); and the propeamussiids *Propreamussium* aff. *pumilum* (Lamarck, 1819) and *Propreamussium laeviradiatum* (Waagen, 1867) (Figure 5C). The non-pectinoids recorded are the ostreid *Actinostreon gregareum* (Sowerby, 1815) and the limoid *Ctenostreon rugosum* (Smith, 1817).

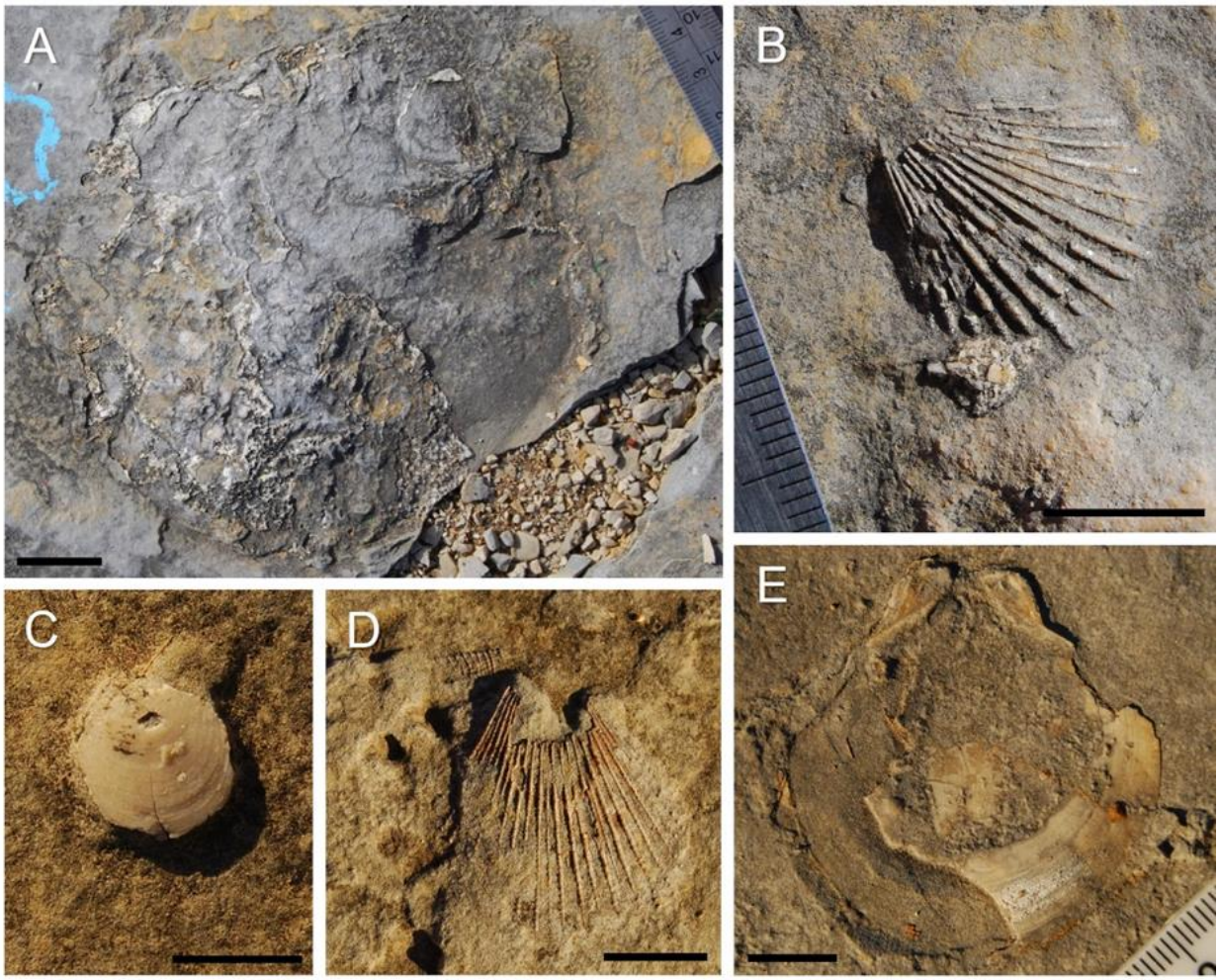

Figure 5. Selected bivalve records from Cabeço da Ladeira site (photos from RP): (**A**) *Eopecten spondyloides* (Roemer, 1836), scale bar is 20 mm; (**B**) *Spondylopecten palinurus* (d´Orbigny, 1850); (**C**) *Propeamussium laeviradiatum* (Waagen, 1867), scale bar: 5 mm; (**D**) *Praechlamys textoria* (Schlotheim, 1820); (**E**) *Entolium corneolum* (Young and Bird, 1828). Scale bar is 10 mm unless otherwise stated.

The nearshore association, which is the interpreted ecological association at the Cabeço da Ladeira paleontological site according to the paleoecology of the other recorded groups and ichnofacies, is represented exclusively by bivalve epifaunal elements. The absence of deep and even shallow burrowing taxa is noticeable and implies a firm substrate predominance which is corroborated by the exclusive epifaunal associations and the relative abundance of *E. corneolum* in some levels. In addition, some relevant presence of cemented forms such as the ostreoid *A. gregareum* confirms the prevalence of firm-to-hardground conditions instead of soft bottom ones. The regular presence of the genus *Spondylopecten*

and *C. rugosum*, which are taxa usually present in reefal associations, gives the perspective of this ecological association nearby. Also, at the top of the stratigraphic sequence, large-sized *C. rugosum* valves functioned as the base structure of buildup communities, wherein serpulid polychaetes are observed.

Gastropods are an intriguing case in the fossil record at the Cabeço da Ladeira site. Their activity is well-attested by the record of the frequent and spectacular *Archaeonassa* trace fossil, but the gastropod body fossils are almost absent. Only a few poorly preserved specimens of pleurotomarids were observed, provisionally attributed to *Pleurotomaria* sp. and *Laevitomaria* sp. morphotypes. *Archaeonassa fossulata* (Fenton and Fenton, 1937) trails demonstrate that, frequently, the behavior of gastropods was to escape from the low-tide dehydration conditions by burrowing into the sediment. That behavior could explain the scarcity of the shell remains at the bed surface and gives perspective as to why they are not fossilized in exposed surfaces of the beds. It should, however, be noted that incipient *Archaeonassa* are produced not only by gastropods, but also by bivalves [21].

The paleoenvironmental conditions were not at all ideal to expect ammonite records (Figure 6). Exceptionally, some phragmocones of large litoceratids (Figure 6B) arrived by nektonic postmortem transportation, besides two tiny inner whorls of stephanoceratids provisionally attributed to *Stephanoceras mutabile* (Quenstedt, 1886) (Figure 6A). More new specimens are needed to confirm this determination. This information is sensible and relevant, as the ammonites are the most accurate chronostratigraphic elements. As mentioned [8], the base of the Chão das Pias Fm. lacks precise dating elements, and for that reason, it was attributed to the lower-upper Bajocian boundary. This determination to those newly collected specimens enables the constraint of the Cabeço da Ladeira biota to the *Humphriesianum* ammonite subzone (*Humphriesianum* zone, top of lower Bajocian), ca. 169.62 Ma [22].

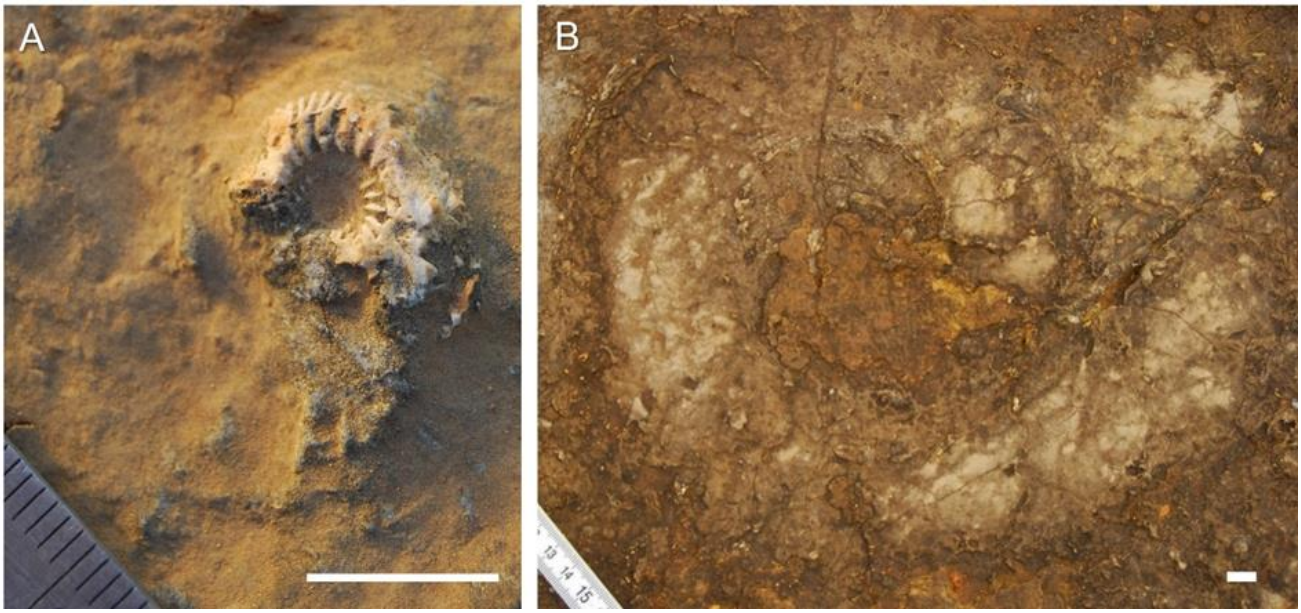

Figure 6. Selected ammonite specimens from the Cabeço da Ladeira site (photos from RP): (**A**) *Stephanoceras mutabile* (Quenstedt, 1886), inner whorls; (**B**) Litoceratidae gen. et sp. indet. Scale bar is 1 cm.

6. The "Jurassic Beach"—Urgent Need for (Geo)Conservation Measures

Cabeço da Ladeira fossils maintain their "spirit of belonging" among the local communities. The former quarry was called the "Jurassic Beach", and signs with this designation were placed from the main road by the municipality, attracting numerous visitors. Since a nearby museum complying with the formalities for safeguarding and studying fossils does not exist, a form of commitment has been established with the local authorities for

the single extraction of key-fossils for research and the work of governmental institutions, local authorities, and scientists to preserve the site as an open-air museum. With this aim, a set of management strategies were devised to make this idea possible, and have since been evolving through time. Soon after finishing the Environmental Recovery Plan, there was a mediatic attention to the site, which led to the attraction of an increasing number of visitors. Until the present day, this geosite is regularly visited by both locals and tourists, as well as organized groups (schools, congresses, tour visits). Since most fossils can only be visible at close proximity, visitors would easily step on them without noticing, leading to fossil deterioration.

The rock succession is exposed to meteorological/erosional factors. Natural surface drainage, the free circulation of visitors outside the recommended path that was established by ICNF, fossil markings using unsuitable materials carried out by non-accredited people, and illegal fossil collection have been factors that contribute to the potential degradation of the Cabeço da Ladeira geosite. Striking a balance between the protection and conservation of this paleontological site and the need for the "Jurassic Beach" to be open to both scientific/educational activities and public enjoyment, with a large, but unknown number of visitors annually, is not an easy achievement. The establishment and implementation of measures to minimize the factors and mechanisms that threaten the conservation of the geological heritage has been a permanent concern among technicians and decision-makers. For any geoheritage, it is strongly recommended to identify geosite values and design management before utilization for education and tourism [23].

A plan has been designed for the geoconservation of the Cabeço da Ladeira paleontological site. Some of the planned measures are as follows: (1) changing the drainage network; (2) avoiding rolling debris on the slab; (3) punctual consolidation of the rock, with possible sealing of fractures in places where it presents a risk of loss of important fossil record with the application of a consolidating and/or water repellent product on paleontological elements and bedding planes; (4) experimental studies in the laboratory and in situ to evaluate the performance (efficacy, harmfulness, and durability) of conservation treatments that may be recommended, prior to the development of the interventions that will be implemented; and (5) establishing and implementing a monitoring plan on a permanent basis to assess the degradation, magnitude of erosion, and weathering factors that act on the bedding planes [24,25].

In addition to the financial investment required to implement these measures in such a large fossil site, there is also no scientific certainty yet about the effectiveness of the application of some products on the local limestone, as well as their possible effects on the rock in the medium- or long-term (Figure 7).

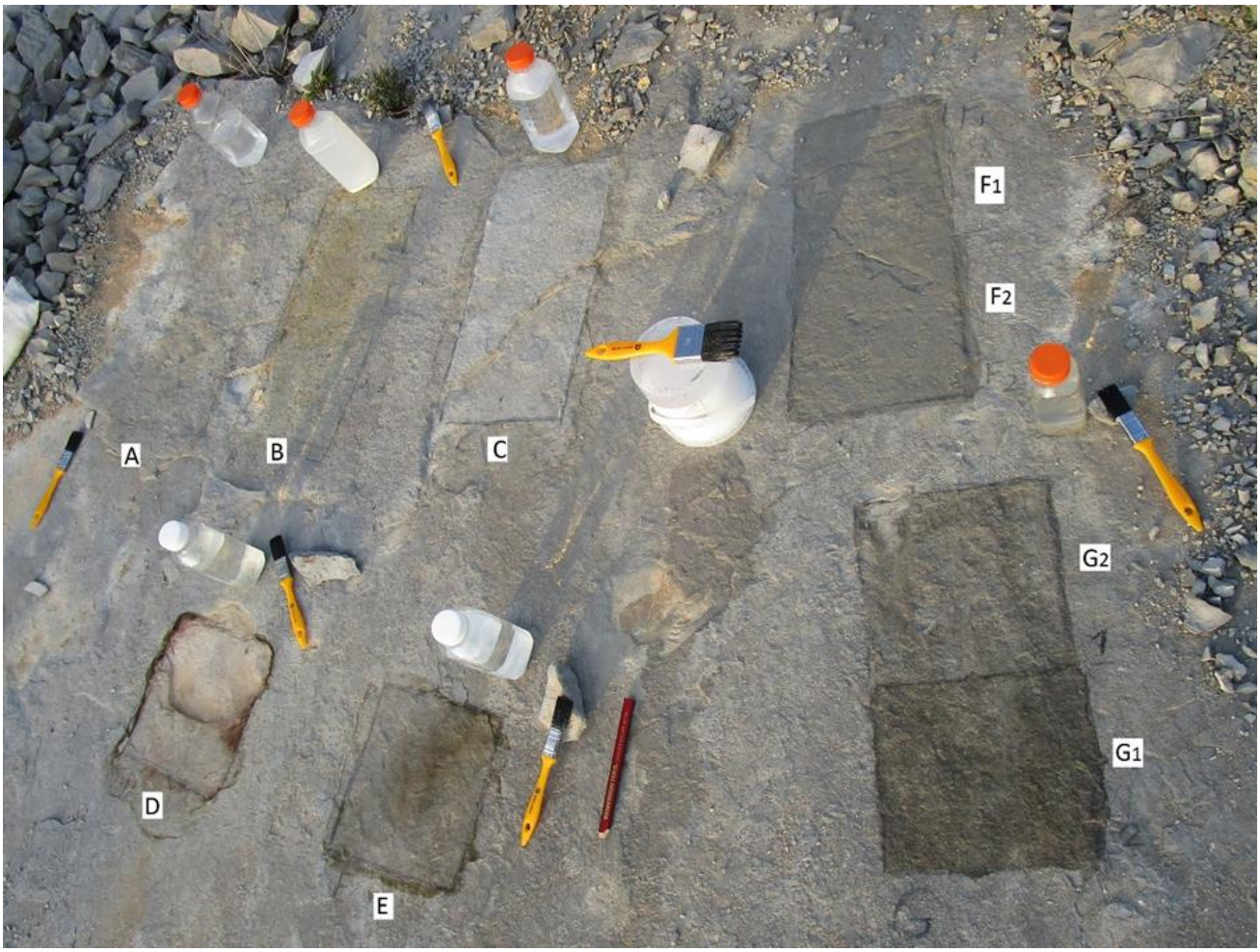

Figure 7. Long-term experiment with application of various products for limestone surface stabilization to weathering in a selected area of Bed 5 bedding plane at Cabeço da Ladeira fossil site: (**A**) lime water (aq.); (**B**) barium hydroxide (aq.); (**C**) ammonium oxalate (aq.); (**D**) solution of barium hydroxide in ethanol; (**E**) ammonium oxalate solution in ethanol; (**F**) nanosilica (upper half—F1—one coating layer, lower half—F2—two coating layers); and (**G**) paraloid B-72 solution in ethanol (upper half—G1—one coating layer, lower half—G2—two coating layers). Dimensions of the areas where the products were applied: 20 × 40 cm and 20 × 20 cm.

In the conservation process in situ, it is essential that the paleontological specimens continue to maintain their integrity and original aspect so that they can continue to be studied by the scientific community. This implies, once again, a balance between the loss of integrity due to the action of weathering/erosion in the rock, and the gain through restorative action, as more efficient and longer-term positive results are found through previously tested local rock exposures following scientific criteria. It is also important to consider that the characterization of the beds that contain the paleontological heritage will serve to complement the descriptions of the paleontological content itself, so any intervention can have consequences. Furthermore, as a result of concerted action between the ICNF, the CMPM, the JFSB, the LNEG, and the scientific researchers—resulting from the need for implementing conservation actions in pursuit of scientific studies—the access to the paleontological site has been restricted by a fence closing the perimeter, and unorganized public visitation is not allowed. The team responsible for the scientific and technical study is available for the development of educational projects, training, and monitoring of guided visits for all levels of education by appointment (Figure 8).

Figure 8. Conservation and outreach actions at the Cabeço da Ladeira geosite (photos from the authors): (**A**) cleaning of the surface; (**B**) execution of casts; (**C**) workshop session at Porto de Mós open to local communities; (**D**) paleontology field trip for students from the Faculty of Sciences, University of Lisbon; (**E**) explanatory panel at the site; and (**F**) internet site at Natural.pt (ICNF).

As one of the approaches for the conservation, valorization, and disclosure of the Cabeço da Ladeira paleontological site, casts have been made, either from the specimens deposited in the Geological Museum (GM) in Lisbon, or from body fossils, trace fossils, and sedimentary structures representative of all the paleobiological features present. These casts—depending on the characteristics of the specimens, such as size and morphological

detail, but also on the conditions of execution, including weather conditions—have been performed in various materials such as silicones and latex. This task has taken place in parallel with the other studies. The specimens deposited in the GM are being casted using fast polymerization silicones and quick-drying latex. They are complementary to the body fossils deposited in the GM, with examples of several meter long trackways and trails that otherwise could not be taken from the outcrop. Two of these casts correspond to plastotypes of the new ichnotaxa *Krinodromus bentou* and *Laterigradus lusitanica* described in [6]. They can be used for developing replicas in an interpretation center. They can also be used in posters used in fixed or travelling exhibitions. For teaching or research, replicas can be equally important in aspects related to accessibility, allowing visitors with locomotive or vision disabilities to appreciate size, shape, and texture comfortably. Replicas can even be beneficial for users without limitations, enabling observation at close range, which will allow for the appreciation of details that at a far distance or with unfavorable lighting conditions would hardly be visible. These conditions for observation using replicas may also be useful on an interpretation trail to be established in the Cabeço da Ladeira paleontological site, as an identification guide and illustration.

Replicas can be executed on a variety of materials, depending on the intended use [26,27]. They may be thin and light, if intended to be fixed to posters either temporarily or permanently, for example for temporary and/or itinerant exhibits. On the other hand, replicas may be thicker and more resistant for handling or permanent display, and may also have characteristics of high hardness, abrasion, and UV resistance, making them suitable for outdoor exposure and greater resistance to vandalism. These different characteristics are possible by selecting from a variety of epoxy, polyester, or acrylic resins, conjugated with various pigments, inert fillers, additives and, when necessary, paints [28].

The preservation and conservation of an open space such as Cabeço da Ladeira involves, of course, several aspects which are complementary and of equal importance. It is necessary to close the space and establish a visitation circuit with the installation of walkways, avoiding indiscriminate access and trampling. Surveillance measures are also needed to prevent abuse and vandalism. The construction of traditional dry-stone walls or the installation of a fence to limit visitation by itself does not guarantee the safety of the site. At the same time, however, it is essential to provide access to those visiting for scientific and educational reasons, and even for organized tourism groups. In an attempt to reconcile these two aspects, the simplest solution seems to be based on the visitor's management of the site by a geographically close entity, for example, the JFSB which, in conjunction with the ICNF, could establish the conditions and times for visitation. It would be possible, for example, to keep it open to the public only on certain days of the week, and to accept appointments for organized group visits. It would be important to ensure that someone is always present to provide information, accept suggestions, guide visitors, exercise some vigilance, and report disturbing situations or those requiring some type of correction. This is a compromise solution. Ideally, a structure should be designed and built to cover and isolate the whole area, sealing it from the agents of erosion, which could eventually also house an interpretation center, research spaces, and facilities for its maintenance. However, such a project would be very costly, not to mention the problems pertaining to material transport, building in a protected area, and a potential negative visual impact. There is still the equally expensive option of cutting, transporting, and reassembling anywhere available—at least the sections representing the various outcropping beds—but this would certainly be a very critical solution, especially for mischaracterizing the site, removing it from the original setting, and thus losing the sense of place that is nowadays considered an added asset for local development [29].

7. Taking the Cabeço da Ladeira Geosite to a New Frontier

As a result of this scientific research and geoconservation strategy, new geoconservation activities have been planned for the short term. These include protection of fossils from weathering and agents of erosion, a new design for a public path, and the establishment

of a visitation program with an emphasis on schools. In addition to the seasonal removal of vegetation that grows in the soil that fills the rock cracks, part of the surface still needs to be cleaned and exhibited, including the removal of some rubble piles that accumulate rainwater, and increased weathering over the bedding planes. Moreover, the study and installation of an effective system for rainwater drainage, as well as the much-needed study of the protection of exposed large surfaces are still under development. Based on the principle that procedures and products can be applied to historical buildings for the conservation and consolidation of carbonates, the application and performance of rock surface conserving products in the Cabeço da Ladeira fossil site should lead to similar results, whether the rock has been used for the construction of a monument or it is in a geological context. Moreover, the treatment of rock in this situation can be a simplified task due to the geotechnical homogeneity of the limestone beds present, as there are not, for example, mortars, plasters, pigments, and metals, as in the constructions made by man. In addition, the location also contributes to a reduction in weathering because it is away from urban centers and pollution.

Meanwhile, the information on the website page [30] was improved, and scientific knowledge has continued to be produced with the detailed mapping of the fossils identified and located using GIS and high-resolution digital photogrammetry.

Photogrammetry is currently one of the methods most used by paleontologists for the survey and 3D modelling of surfaces and objects of study, as it has a high capacity for making accurate, complete, and highly realistic records [31,32]. The models produced—besides corresponding to important digital safeguard records—allow for their study in an office environment and enable their dissemination through various digital platforms. Some examples of the photogrammetric modelling of the body and trace fossils that have been carried out for registration, study, and future dissemination are provided (Figure 9). Photogrammetric models can be 3D printed, resulting in accurate physical copies of the fossil record. This means that a fossil from Cabeço da Ladeira can be emailed or sent by post for research or outreach purposes.

The systematic study of the paleontological site, at multiple scales, allowed the digitalization of the entire exposed area. This allows for precise pinpointing of the location of all fossils and sedimentary structures present at the bedding plane exposures and, also, to serve as a digital record of the entire succession. This digital copy can also serve as an educational tool, as it will allow for virtual tours around the site.

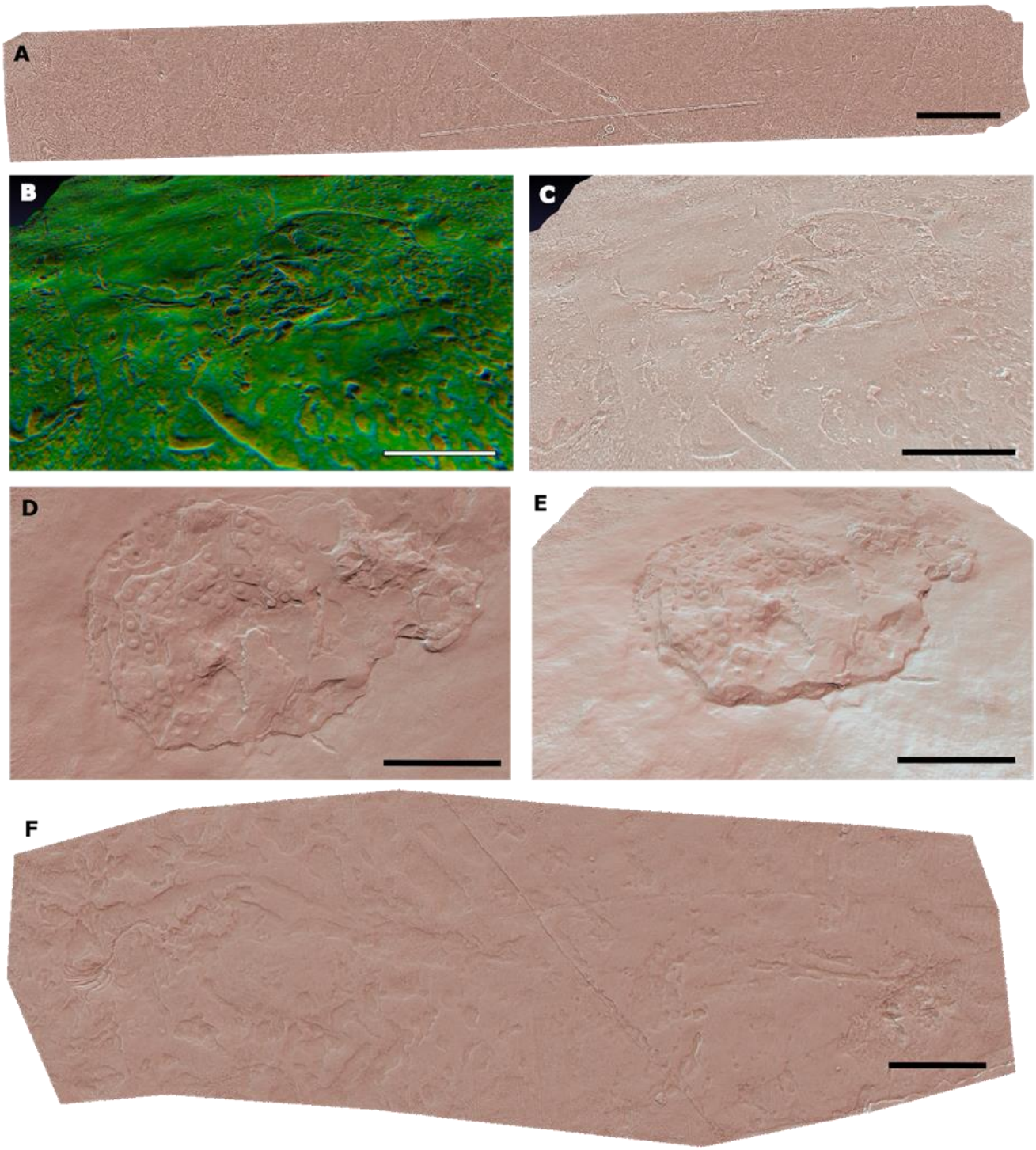

Figure 9. The 3D photogrammetric modelling of the most relevant body and trace fossils (generated by J.B.). (**A**) Trace fossil representing swimming behavior; scale is 50 cm. (**B**,**C**) Resting trace of a Rhinobatidae; scale is 25 cm. (**D**,**E**) Vertical and oblique 3D views of a *Heterocidaris*; scale is 5 cm. (**F**) Vertical view of the *Krinodromos bentou* 3D model revealing the agonistic trail left by a stalked crinoid; scale is 25 cm. Model B is highlighted by the application of shadows and curvature map. Warm tones correspond to concave areas and cool tones to convex areas. The remaining models presented are highlighted by the radiance scaling method [33].

8. Conclusions

The geoconservation of the Cabeço da Ladeira paleontological site at the PNSAC protected area in central Portugal—dated likely from the top of the lower Bajocian (*Humphriesianum* zone)—is complex due to the high sensitivity of its geological heritage, consisting of an outstanding body and trace fossil record of international relevance (Figure 10) exposed in a widely accessible surface divided by seven beds of a former quarry. Consequently, in the last years, fossils have been widely exposed to extreme climatic factors, trampling, and vandalism, which cannot be actively dampened because of the lack of formal organized visits and a permanent guardian. Moreover, and above all, geoconservation has been hindered so far by the difficulty to orient financial and human resources to the fossil site, despite the efforts of all those involved. Despite the constraints, the process of scientific study and conservation of the site has not stopped and has focused on closer cooperation and the establishment of synergies between all institutions involved, including scientists, local authorities, municipal technicians, and the local community. These groups have worked together in the establishment of a plan for sustainable actions in the short and medium terms, and a fruitful dialogue with populations through the organization of public sessions and formal field excursions during international congresses and for universities, as well as informal visits to the geosite during research field work.

Figure 10. Reconstruction of the Cabeço da Ladeira tidal flat ecology based on the remarkable record of body and trace fossils of early? Bajocian age. Body fossils and biogenic structures represented: (1) Starfish including *Noviaster*; (2) pleumotomarid gastropod; (3) *Arenicolites,* crustacean burrow; (4) *Archaeonassa,* gastropod trail; (5) *Laterigradus lusitanica,* crab trackway; (6) cidaroid; (7) cidaroid track; (8) guitarfish; (9) *Piscichnus*, ray feeding burrow; (10) lithoceratid ammonite; (11) *Krinodromus bentou*, crinoid trail; (12) isocrinid crinoid; (13) *Undichna*, fish trackway; (14) microbial mat.

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