

The Enigmatic Upper Ordovician of the Naturtejo UNESCO Global Geopark (Portugal)

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Abstract

Naturtejo UNESCO Global Geopark (Portugal) area includes deposits from the Neoproterozoic to the Quaternary. Despite its limited exposure area in major Variscan folded structures, the Ordovician series hosts some of its most famous geological heritage features, such as the Penha Garcia Ichnological Park. The Upper Ordovician of the Central Iberian Zone is still far from being as well-understood as it is in other areas. Extensional tectonics, magmatism, global eustatic and climatic changes generated a great variability of sequences in a reduced geographical area. The Upper Ordovician of the Naturtejo region, often considered poorly represented, is here demonstrated to have a great potential and to be more complete than previously assumed. New stratigraphic and paleontologic data are presented for the three Upper Ordovician-bearing structures within Naturtejo: Fajão-Muradal, Vila Velha de Ródão and Penha Garcia synclines. Remobilized upper Katian fossiliferous clasts were found for the first time within the Hirnantian Casal Carvalhal from the Fajão-Muradal Syncline and a new fossil site is added to the Orvalho GeoTrail. In the Vila Velha de Ródão Syncline, the Barroca da Senhora stream fossil site constitutes a new geosite within the protected area of Portas de Ródão Natural Monument, presenting the most complete Upper Ordovician sequence of this structure. Finally, the stratigraphic and paleontologic record of the Vale Feitoso estate offers all the conditions to propose a new theme geotrail, diversifying the tourism in the Monfortinho village (Penha Garcia Syncline).

Keywords: Fajão-Muradal, Vila Velha de Ródão, Penha Garcia, Nicolella Fauna, Kralodvorian, High-Latitud peri-Gondwana, BODA Event, Central Portugal

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Introduction

Naturtejo UNESCO Global Geopark, the first established in Portugal, joined the European and Global Geoparks networks under the auspices of UNESCO, in 2006. It was included in the International Geosciences and Geoparks Program of UNESCO in 2015 as a territory of 5067km², covering seven municipalities: Castelo Branco, Idanha-a-Nova, Nisa, Oleiros, Penamacor, Proença-a-Nova, and Vila Velha de Ródão. The Naturtejo Geopark geological heritage is represented by deposits from the Neoproterozoic to the Quaternary, the Ordovician successions being among its main features, exposed in large Variscan-folded structures and representing some of its most famous geosites (e.g., the Penha Garcia Ichnological Park and the Portas de Ródão Natural Monument).

When comparing with other Ordovician series, the Upper Ordovician of the Central Iberian Zone (CIZ) remained largely unknown through more than one century of geological studies. In the second half of the 20th century, there was a great increase in the knowledge of the Portuguese Upper Ordovician, and modern lithostratigraphic schemes were established (e.g., Mitchell 1974; Romano & Diggens 1974; Paris 1979; Cooper 1980, Young 1988). Despite some advances in the last 15 years (e.g., Sá *et al.* 2005; Romão 2006, Vaz, 2010; Meireles 2011; Pereira 2017), we are still far from knowing the true extent and architecture of Portuguese Upper Ordovician deposits. As a result of global eustatic variations, related to tectonics, a global warming event and a glaciation (e.g., Brenchley *et al.* 1991; Hamman 1992; Fortey & Cocks 2005), the Late Ordovician breaks with an apparent monotony and constancy that characterized sedimentation during Early and Middle Ordovician epochs in the CIZ. Late Ordovician extensional tectonics may have controlled accommodation space of the post-Sardic sedimentation (e.g., Álvaro *et al.* 2016), and the related magmatism generated interbedded sequences of volcanic or volcano sedimentary rocks interbedded in Katian fossiliferous sediments (e.g., Porto

de Santa Anna Formation). Erosion or non-deposition significantly reduced the representation of the Upper Ordovician within CIZ and produced a great variability of sequences. So far, in Portugal, this system has been recognized in a total of 12 structural/geographical sectors (Pereira 2017), three of them occurring within the Naturtejo Geopark's area: the Fajão-Muradal, Vila Velha de Ródão and Penha Garcia synclines. Despite their geographical proximity, these three sequences are significantly different, being a challenge not only to correlate but especially to interpret their depositional and basinal topographic settings and geodynamic evolution. Thus, their fossil content is essential for the recognition and the improvement of our understanding of these rather enigmatic sequences.

Herein, we present the state of the art of the Upper Ordovician fossil record within the Naturtejo Geopark area and the most recent advances on the stratigraphy and palaeontology of this series. This work aims to represent a bridge between scientific research within a geopark and its recognized geoh heritage, contributing to unravel and expand the geoscientific offering of Naturtejo while providing a field-laboratory for researchers.

Geological settings and background of Naturtejo Geopark Upper Ordovician Sequences

The studied area belongs to the Central Iberian Zone (CIZ) of the Iberian Massif, corresponding to post-Cambrian metasedimentary sequences that lie in angular unconformity on the Beiras Group (upper Ediacaran -?lower Cambrian). Five NNW-SSE to WNW-ESE major Variscan folded structures preserving lower Paleozoic successions occur within the Geopark: the Fajão-Muradal, Vila Velha de Ródão, Penha Garcia, Castelo Branco – Unhais-o-Velho and Monforte da Beira areas. This study focuses on the first three, where Upper Ordovician levels have been recognized up to now (Figs. 1, 2).

Having gone unnoticed during several decades

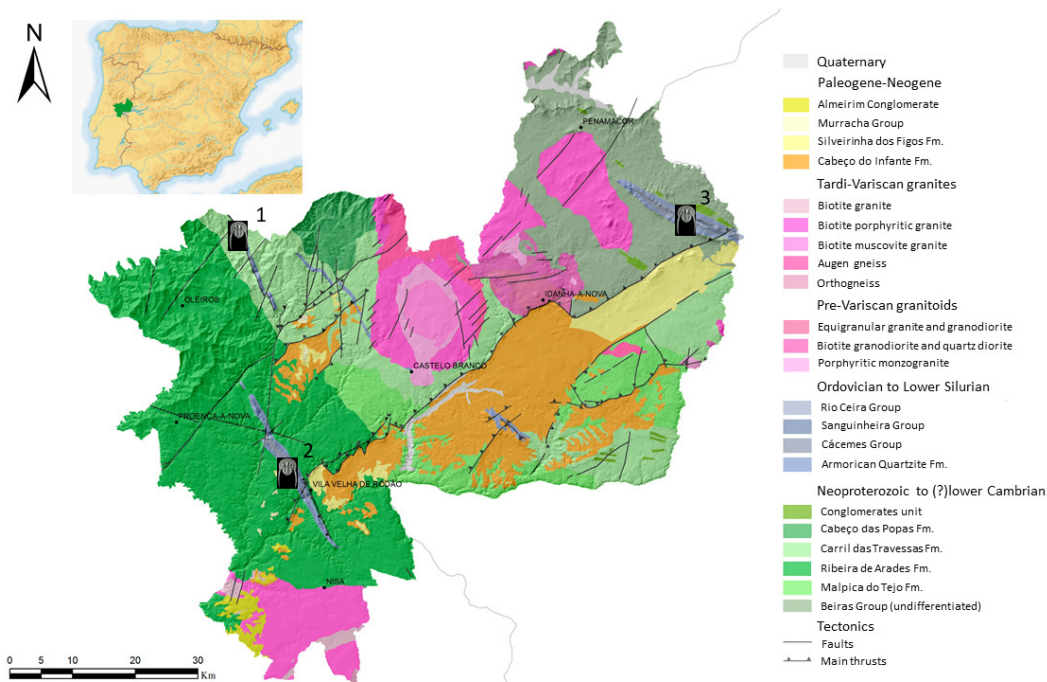


Figure 1. Simplified geological map of the Naturtejo UNESCO Global Geopark (adapted from the 1:500000 map published by Serviços Geológicos de Portugal in 1992) with the location of the three structures indicated in the text: 1 – Fajão-Muradal Syncline; 2 – Vila Velha de Ródão Syncline; 3 – Penha Garcia Syncline.

of geological studies in Portugal (e.g., Delgado 1908; Costa 1931; Teixeira 1955), the Upper Ordovician of the Naturtejo area has been discovered little by little. In the Fajão-Muradal Syncline, Thadeu (1951) correctly recognized some ‘clay-sandstone shales’ and ‘dolerites’ as being ‘Caradocian’ in age (mostly corresponding to the Berounian stage of the Ibero-Bohemian Regional Scale), but other important successions had to wait much longer to be identified: in the Penha Garcia Syncline the Upper Ordovician was being progressively recognized from the seventies on (Perdigão 1971; Romano 1982; Young 1985) and in the Vila Velha de Ródão Syncline only recently (Metodiev *et al.* 2009). Among these, only the chronostratigraphic assignment of the Penha Garcia sequence was supported by fossils (Young 1985), the remaining sequences being attributed to the Upper Ordovician based solely on their stratigraphic position and regional lithostratigraphic correlation.

In the last decade, work conducted by the authors led to the discovery of the first Upper Ordovician fossil assemblages from the Vila Velha de Ródão and Fajão-Muradal synclines (Pereira *et al.* 2015; Pereira 2017; Pereira *et al.* 2017) and the revelation of more complete sequences than were previously thought to exist. The Upper Ordovician of Naturtejo region, often considered absent or poorly represented, is here demonstrated to have a great potential to improve the knowledge of the geodynamic evolution of the CIZ.

Stratigraphy and Paleontology: New Data and Research Lines

1. Fajão-Muradal Syncline

Only the southern half of this long (32 km) and narrow (about 1 km) Variscan structure lies within the Naturtejo area, roughly south of the Zêzere River (site 1 in Figure 1). In the most detailed work

GLOBAL			REGIONAL		FAJÃO-MURADAL SYNCLINE (1) Young (1985, 1988); Metodiev <i>et al.</i> (2010); this work	VILA VELHA DE RÓDÃO SYNCLINE (2) Metodiev <i>et al.</i> (2009); this work	PENHA GARCIA SYNCLINE (3) Young (1985, 1988); Sequeira <i>et al.</i> (1999)	
SERIES	STAGE	stage slices	Mediterranean and N. Gondwana (Bergström <i>et al.</i> , 2009)					
UPPER ORDOVICIAN	HIRNANTIAN	Hi2	HIRNANTIAN (=KOSOVIAN)		Casal Carvalho Fm	? Casal Carvalho Fm		
		Hi1						
	KATIAN	Ka4	KRALODVORIAN	u.	Porto de Santa Anna Fm	Ferradosa Fm (remobilized)		
		Ka3		l.				
		Ka2	BEROUNIAN	upper	? Ribeira da Laje Fm	? Ribeira da Laje Fm	Ribeira da Laje Fm	
		Ka1				Vaca Mb		
	SANDBIAN	Sa2	BEROUNIAN	mid.	Louredo Fm	Louredo Fm	Louredo Fm	
		Sa1		lower				
				DOBROTIVIAN	upper			
				lower				

Figure 2. Synthetic chart of the Upper Ordovician litho-chronostratigraphic units recognized in the studied structures of the Naturtejo UNESCO Global Geopark (it does not represent a stratigraphic log); the main lithostratigraphic contributions are cited for each sector.

on this syncline (Metodiev *et al.* 2010), the Paleozoic succession is considerably more incomplete in the southern sector, represented mainly by the ‘Armorican Quartzite’ (Serra do Brejo Formation; Arenigian stage, Lower-Middle Ordovician). In the northern sector, the sequence is preserved up to the lower Silurian. Herein we present a mostly continuous section west of Orvalho, allowing the recognition of a more complete Ordovician record within a previously already established geosite

(Ribeira do Orvalho geological section; Neto de Carvalho *et al.* 2013). Materials derived from the Ferradosa Formation were recognized for the first time in the Fajão-Moradal Syncline, remobilized within a diamictitic Hirnantian unit (Casal Carvalho Formation). They are represented by limestone clasts bearing a diverse fossil assemblage of Kralodvorian age (upper Katian, Ka3-4), including brachiopods, trilobites, machaeridians, bryozoans and echinoderms (Fig. 3S-W). Deposition of the Fer-

radosa Formation is related to the global warming BODA event (Fortey & Cocks 2005). Because of rising temperatures, carbonate sedimentation encroached upon high-latitude peri-Gondwana and low-latitude taxa (e.g., brachiopod genus *Nicolella*, Figure 3S) expanded their geographical distribution into this province (Colmenar *et al.* 2017). The Portuguese Kralodvorian sedimentary record is extremely scarce, being mostly absent in the remaining CIZ of central Portugal. The new data suggest that its absence is more related to an important Late Ordovician erosion event (probably associated with the Late Ordovician Glaciation), rather than to non-deposition. Furthermore, this section also provides new insights on the basin paleotopography and sediment source of post-Kralodvorian deposits within the CIZ. All regional and global Upper Ordovician stages are now known to be represented in the Fajão-Muradal syncline (Figure 2): the Louredo Formation (middle Berounian; Sa2-Ka1), ?Ribeira da Laje Formation (upper Berounian, K2), Porto de Santa Anna Formation (upper Berounian-?Kralodvorian; Ka2-3), remobilized Ferradosa Formation (Kralodvorian; Ka3-4), and Casal Carvalhal Formation (Hirnantian). Thus, this sector preserves the second most complete Upper Ordovician record of Portugal.

2. Vila Velha de Ródão Syncline

This 30 km-long syncline is relatively wider (2.5 km) than the Fajão-Muradal structure, and contains a more complete Ordovician-Silurian sequence. The geological mapping produced by Metodiev *et al.* (2009) significantly improved the lithostratigraphical knowledge of this sector. The studied sequence is located at the Barroca da Senhora stream (Metodiev *et al.* 2009, Figure 2 – Cabeço da Achada), in the northeastern limb of the syncline and it is, at present, the most complete Upper Ordovician record within this syncline (Figure 2). Fossils were only found at the base of the Louredo Formation, although scarce, but including a new trilobite (*Primaspis* aff. *primordialis*; Figure 3A) also known from the Amêndoa-Carvoeiro Syncline (Pereira 2017). Despite the proximity to

this latter structure (less than 20 km), the Upper Ordovician of the Vila Velha de Ródão Syncline is surprisingly different. The bryozoan-mudstone beds of the Cabeço do Peão Formation are here replaced by the sandstones of Louredo Formation, just like in the Fajão-Muradal Syncline. Nevertheless, the Kralodvorian succession of the latter is absent at Vila Velha de Ródão and the succeeding Hirnantian sequence is poorly understood: it was previously assigned to the Casal Carvalhal Formation, based on its typical spheroidal weathering (Metodiev *et al.* 2009), but in our fieldwork campaigns we did not recognize those levels as representing this unit.

3. Penha Garcia Syncline

Famous for hosting one of the most important geosites of Naturtejo, and possibly the most impressive forms of *Cruziana* worldwide (Penha Garcia Ichnological Park), this syncline is 21.5 km long in Portugal, with an average width of 2 km. Contrary to the previously described structures, the Penha Garcia Syncline sequence finishes in the Upper Ordovician, overlapped by Cenozoic deposits. The youngest unit recognised at present is the Ribeira da Laje Formation of upper Berounian (Katian, Ka2) age (Figure 2). A diverse fossil assemblage from the Louredo Formation is herein reported from a fossil site discovered by Neto de Carvalho *et al.* (2014), within the private estate of Vale Feitoso. It is dominated by trilobites (*Deanaspis seunesi*, *Crozonaspis dujardini* and *Dalmanitina* sp.) and brachiopods (*Aegiromena aquila aquila*, *Svobodaina havliceki* and *Lingulidae* indet.), with fewer molluscs (*Praeleda ribeiroi*, *Holopea?* sp.) and trepostomate bryozoans (Fig. 3B–M). Curiously, a mudstone unit (the Vaca Member) is present in the same estate, unique within the Naturtejo area and correlated with the Galhano Member of the Buçaco Syncline (Young 1988). Its fossil assemblage (Fig. 3N–R) remains unstudied (it was preliminarily presented by Young 1985) and includes some unique occurrences within Portugal, such as the brachiopods *Kjaerina* (*Kjaerina*) *gondwanensis* and *Rafin-*

esquina (Mesogeina) pseudoloricata. It is particularly important to understand better deeper marine communities from offshore environments of the peri-Gondwanan late Berounian, usually represented by shallower, shoreface environments. The presence of a poorly exposed thin oolitic ironstone occurring above the Vaca Member, which Young (1988) referred to the basal Leira Má Member of the Porto da Santa Anna Formation of the Buçaco Syncline, is also unique within the Penha Garcia syncline. The recent assignment of the Ribeira da Laje Formation to the upper Berounian (Vaz 2010), instead of Hirnantian, as originally proposed by Young (1988), makes this correlation problematic: this oolitic ironstone at the top of the Vaca Member is overlaid by the Ribeira da Laje Formation. Until a broader understanding of the Ribeira da Laje Formation has been achieved in its type area (Amêndoa-Carvoeiro Syncline), the age of this unit must be treated carefully. In the Penha Garcia Syncline, the Ribeira da Laje Formation shows a rare occurrence in the Upper Ordovician of CIZ of bioturbation composed by mostly mm-scale, horizontal simple burrows and *Nereites missouriensis* in simple shallow tiers, which seems to show sporadic colonization of dysoxic bottoms by minute foragers. Further investigation will allow clarifying what really happened during Late Ordovician in Penha Garcia area.

Geotourism and Geotrail Potential of the New Upper Ordovician Geosites

Ongoing work reveals a much higher potential of Upper Ordovician sequences of Naturtejo Geopark than previously considered. The Fajão-Muradal Syncline contains the second most complete Upper Ordovician record in Portugal and documents important environmental changes related to a global warming event that preceded the Late Ordovician glaciation, which likely triggered one of the deadliest mass extinctions in the history of life on Earth. The new fossil site is located within the Orvalho GeoTrail, recently improved by the building of walkways that provided access to a series of Geopark's classified geomonuments, such as

the Fraga de Água d'Alta waterfall and Cabeço do Mosqueiro geomorphological viewpoint, attracting thousands of visitors. Its inclusion within this geotrail is a great opportunity not only to discuss the climate changes occurring in the past (the clasts reminiscent of a global warming carbonate event enclosed within sediments including diamictites in the Casal Carvalhal Formation, and deposited in high-latitude settings during a glacial period) and their impact in the ecosystems (the Late Ordovician Mass Extinction was the second largest known with the elimination of nearly 85% of marine species), but also constitutes a pedagogical section for students and a field-laboratory for researchers. The study of the fossil site should be intensified under the control of the local authorities and conservation measures must be implemented regarding the access of the GeoTrail users. The new Environmental Interpretative Centre of the Orvalho GeoTrail, in the historical core of the village, would be the right place to integrate the collection of fossils recovered. This is an opportunity to develop an exhibition dedicated to education on the impacts of climate change upon biodiversity (mass extinctions) and society (social and economic impacts and adaptation), within the framework of the United Nations Sustainable Development Goal 13 - Climate Action.

On the other hand, recent advances in the study of the Upper Ordovician sequences of Vila Velha de Ródão and Penha Garcia synclines open an opportunity further to understand the record of this series within Naturtejo Geopark area and the geodynamic evolution of the CIZ during the Ordovician period. The Barroca da Senhora stream fossil site is a new geosite within the protected area of Portas de Ródão Natural Monument and the collected fossils will be included in the collections of the Municipal Museum. The museum is now under a renovation project that will assure the interpretation of the Natural Monument. The ongoing work, particularly in the 7000 ha Vale Feitoso estate, has all the conditions to develop a new theme geotrail. Its stratigraphic and paleontological heritage will

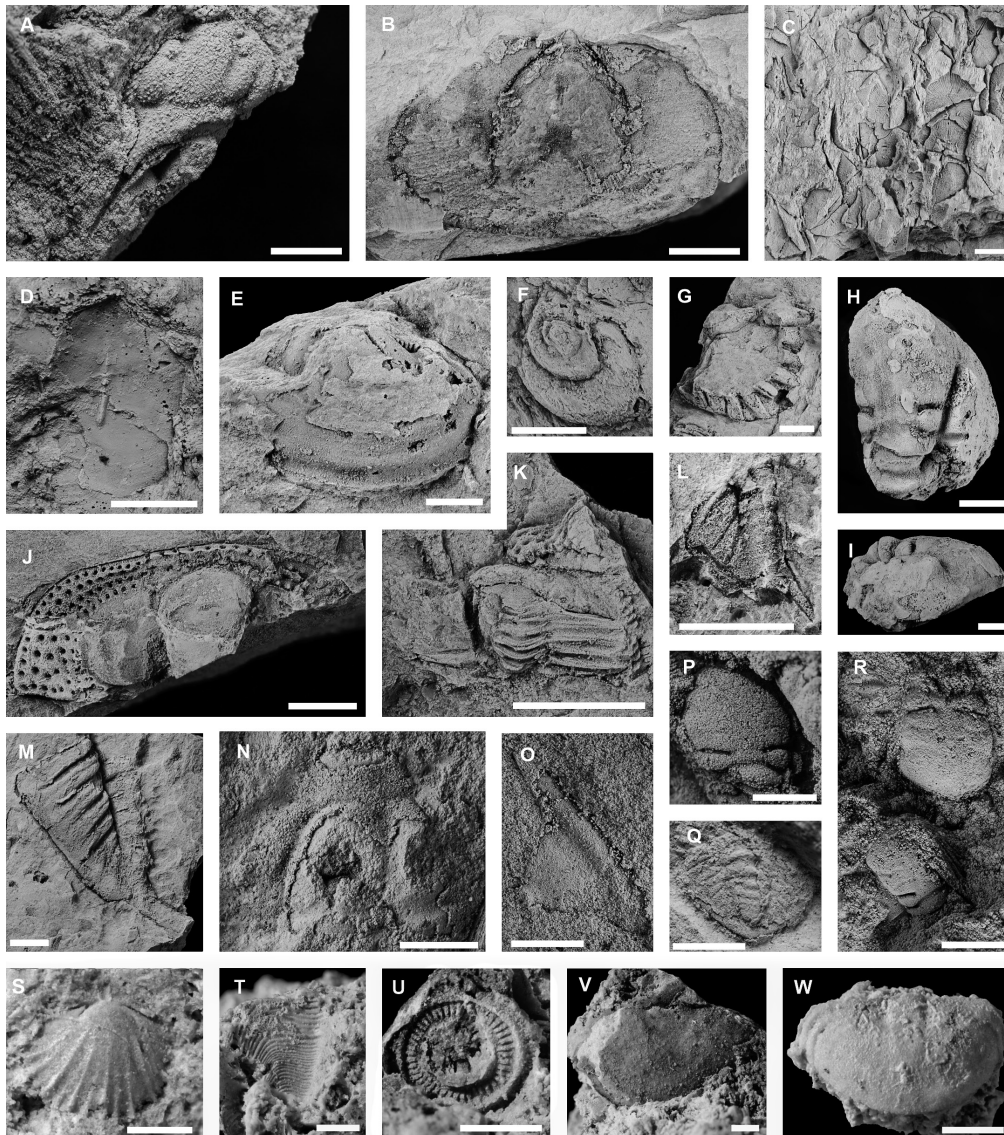


Figure 3. Upper Ordovician fossils from the Naturtejo Geopark: Louredo Formation (middle Berounian, ca. Sa2-Ka1) of Vila Velha de Ródão Syncline (A) and Penha Garcia Syncline (B-M); Vaca Member (upper Berounian, ca. Ka2) of Penha Garcia Syncline (N-R) and Ferradasa Formation (Kralodvorian, ca. Ka3-4, remobilized within Hirnantian Casal Carvalhal Formation) of Fajão-Muradal Syncline (S-W). A) *Primaspis* aff. *primordialis* (Internal mold, dorsal view of a cranidium). B) *Svobodaina havliceki* (Internal mold, ventral valve). C) *Aegiromena aquila aquila* (several internal and external molds). D) Lingulidae indet. (External mold, dorsal valve). E) *Praealeda ribeiroi* (Internal mold, left valve). F) *Holopea?* sp. (Internal mold, apical view). G-J, *Crozonaspis dujardini* (Internal molds, H-I, dorsal and lateral views of a cephalon, G) Lateral view of a partially enrolled thorax and L) dorsal view of a pygidium). J-K, *Deanaspis seunesi* (Internal molds: J) Dorsal view of a cephalon and K) An enrolled exoskeleton). M) *Dalmanitina* sp. (Dorsal view, internal mold of a pygidium). N-O, *Calymenella boisseli* (Dorsal view: N) Cranidium and O) Right librigenal). P-R, *Kloucekia* sp. cf. *Dreyfussina exoptalma* (dorsal views: P) and R) cranidia and Q) pygidium). S) *Nicolella* sp. (Internal mold, juvenile ventral valve). T) *Plumulites* sp. (External mold). U) *Pentagonocyclicus* (col.) sp. (External mold of a columnal plate); V-W, Illaenidae indet. (Internal mold, dorsal view: V) pygidium and W) Meraspid pygidium). All scale-bars=5mm, except S-W (=2mm).

illustrate what happened in the Ordovician times after the famous *Cruziana* beds at the Penha Garcia Ichnological Park were formed while offering a reuse for the unique landscape of Vale Feitoso, diversifying the tourism offering of the Termas de Monfortinho thermal village. The new Interpretative Centre under development at Penha Garcia will include fossil collections and the research results in the permanent exhibition.

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Conflict of Interest

The authors declare to have no conflict of interest

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