

Giant Trilobites and Other Middle Ordovician Invertebrate Fossils from the Arouca UNESCO Global Geopark, Portugal

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Abstract

The giant Ordovician trilobites from the Canelas quarry constitute the most iconic sign of identity of the Arouca UNESCO Global Geopark at an international level. Palaeontological studies determined the importance of this fossil locality for studying aspects of the social behavior of these marine arthropods and their interactions with other represented invertebrate fossil groups. Although part of the famous ‘gigantism’ of the fossils represented in the slate quarry is due to tectonic expansion, which is responsible for one-third of the outstanding size of the fossils, there is no doubt that this locality, sometimes considered as a fossil lagerstätte, has a great scientific interest and represents a unique international reference among the geological heritage of Portugal. The construction of an on-site museum and the establishment of a geotrail around the quarry have turned this geosite into an example of cooperation between extractive industry, education, science and sustainable development. The formal partnership established with the AGA–Arouca Geopark Association reinforces the projection of this geosite, allowing its disclosure in exhibitions and educational programs, as well as the collaboration with the scientific community.

Keywords: Arouca UNESCO Global Geopark, Ordovician geosite, Canelas slate quarry, Giant trilobites, Geoheritage, Geoconservation, Geotourism, Sustainable Development.

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Introduction

The Palaeozoic outcrops of the Arouca UNESCO Global Geopark (Arouca UGGp) belong to the Central-Iberian Zone of the Iberian Massif, located in the south-eastern prolongation of the Valongo Anticline, within a structure that extends eastwards to Spain. The Ordovician strata unconformably overlie the Douro-Beiras Supergroup, a thick schist-greywacke sequence of Neoproterozoic to middle Cambrian age. It comprises three lithostratigraphic units and the Santa Justa Formation is considered as the oldest of late Early Ordovician (Floian) age. It is a relatively thin (35–60 m) quartzitic unit representative of the widespread ‘Armorican quartzite’ facies of southwestern Europe. The Middle Ordovician (Dapingian to Darriwilian) Valongo Formation, a 430 m thick, homogeneous and fossiliferous succession of shales and siltstones, which includes roofing slates of commercial quality is overlying the quartzites. Siliceous nodules are common, especially at the top of the unit, and a thin distinctive ferruginous horizon (5–20 cm thick) occurs in the middle part of this formation. An erosive paraconformity separates the Valongo Formation from the overlying Sobrido Formation, of the late Ordovician (Hirnantian) age. The latter comprises a prominent basal quartzite unit (about 8 m thick) underlying massive silty diamictites (about 10 m thick in the studied area),

where reworked dropstones (ranging from a few millimeters to a few centimeters in diameter) of glaciomarine origin occur. These glaciomarine strata are conformably overlain by Silurian (Llandovery) black shales.

The Ordovician outcrops near Arouca were first studied in some detail by Thadeu (1956), who described a diverse assemblage of trilobites, graptolites and brachiopods from the Canelas old slate quarry, which was assigned to the ‘Llandeilian’. Recent taxonomical and biostratigraphical reappraisals (Sá & Gutiérrez-Marco 2006; Sá *et al.* 2007), due to the re-opening and enlargement of the Canelas quarry in 1990, revealed that most of the trilobite occurrences came from the middle part of the Valongo Formation, in the best quality roofing slate beds. These fossiliferous levels are of the middle of the Darriwilian age (*Didymograptus artus* graptolite biozone). Among the trilobites, several giant specimens brought growing popularity to this fossil locality (Gutiérrez-Marco *et al.* 2009; Guy & Lebrun 2010; Figueiredo 2011; Rábano *et al.* 2014), which resulted in providing one of the indisputable signs of identity to the geosites located in the Arouca Geopark (Sá *et al.* 2006, 2008, 2009, 2011b, Rocha *et al.* 2008, 2014).

Location

The Canelas slate quarry is located 50 km south-

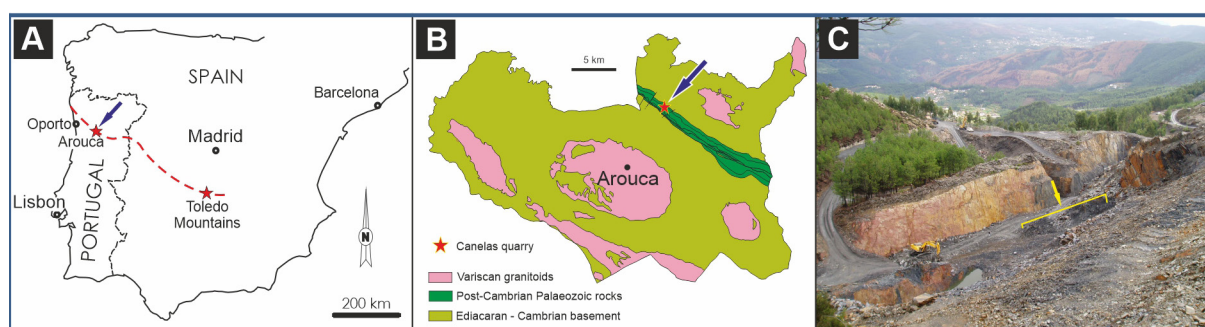


Figure 1. The location of the Arouca Geopark and the Canelas palaeontological geosite on a map of the Iberian Peninsula, A) showing the continuity (dashed line) of the fossiliferous bed into the Spanish region of Toledo Mountains. B) Location of the Canelas quarry on a general geological sketch map of the Arouca Geopark (arrow). C) Field photograph of the main trilobite-bearing slate bed (framed by the yellow line pointed by the arrow), taken from the southwest.

east of the city of Oporto, in the north-eastern part of the Arouca UGGp (Figs. 1A–C), approximately 4.2 km NE of Arouca town. The exploited beds with mid-Darriwilian trilobite assemblages occur from 90 to 240 m above the base of the Valongo Formation. These include 15 trilobite genera, belonging to four different orders (Sá & Gutiérrez-Marco 2006; Sá *et al.* 2007), together with cephalopods and graptolites, rare hyolithids, gastropods, bivalves, rostroconchs, brachiopods, and echinoderms, which are only more frequently recorded in the upper beds (Sá & Gutiérrez-Marco 2006, 2009). Additionally, a rather diverse ichno-assemblage also occurs in the quarried beds (Sá & Gutiérrez-Marco 2006, 2015; Neto de Carvalho *et al.* 2016; Gutiérrez-Marco & Sá 2016; Sá *et al.* 2016).

Next to the quarry, the owner company – Ardósias Valério & Figueiredo Lda – has built an on-site museum, the Geological Interpretative Centre of Canelas (CIGC), open since July 2006. The most famous and spectacular fossils obtained in the industrial exploitation are displayed in its exhibition.

Significance of the Canelas Ordovician Geosite

The Ordovician palaeontological site of the Valongo Formation at the Canelas quarry is outstanding in having provided some of the world's largest trilobite fossils (Sá & Gutiérrez-Marco 2006). A special mention is due to the particular gigantism in six different species (Fig. 2A), as well as numerous samples of monotaxic and polytaxic size-segregated autochthonous trilobite clusters, which have demonstrated a wide array of ethology shown by these marine arthropods. Synchronized gregarious behavior for moulting and/or mass mating in five trilobite families, belonging to three different orders, coexists in this single locality, and also the inferred cryptic behavior through some linear clusters, suggesting those trilobites were looking for temporary refuge from predation, among other reasons (Gutiérrez-Marco *et al.* 2009).

The most common trilobites in the assemblage

are the calymenines *Neseuretus avus* (Fig. 2C), the *Bathycheilus castilianus*, and the illaenid *Ectillaenus giganteus*, all of which are typical of shallow marine environments in periods of normal bottom oxygenation. However, extended intervals of anoxia related to water stratification, intermittently produced dysaerobic conditions on the seafloor that had the ability for mass killing (e.g. those clusters of moulting trilobites). These temporary dysaerobic environments were only inhabited by unknown specialized burrowers and large opportunistic trilobites, such as the asaphid *Ogyginus forteyi* (Fig. 2A) and the otherwise rare dikelokephalid *Hungioides bohemicus* (Fig. 2B), a genus recorded throughout the peri-Gondwanan Europe and as far as the Indo-China Terrane (Fatka *et al.* 2008). Among nektonic organisms, large longicone nautiloids, whose shells were about 1 m in length (Sá & Gutiérrez-Marco 2009), occasionally preyed on trilobites, producing triangular bite marks (ichnogenus *Bicrescomanducator*) which are now preserved on their exoskeletons (Sá & Gutiérrez-Marco 2015).

The influx of shelf currents would end those successive periods of stagnation, allowing the settling of an endo- and epibenthic community represented by a normally oxygenated trilobite fauna, brachiopods (*Paralenorthis*, Cremnorthidae), bivalves (*Coxiconchia*, *Babinka*, *Redonia*, *Praenucula*), rostroconchs (*Ribeiria*, *Tolmachovia*), gastropods (*Sinuites*), hyoliths (*Elegantilites*, *Recilites?*), echinoderms (*Calix*, *Codiacystis*, *Ranunculocolumnus*, *Palaeura*), and conulariids (*Archaeoconularia*). Nevertheless, the diversity of this typical middle Darriwilian assemblage is quite reduced, in comparison with those from coeval strata in Spain or western sectors of the Valongo Formation. This can be related either to the low duration of normal oxygenation intervals between anoxic events or to the sediment type, less clayey and favorable for infaunal and semi-infaunal organisms. In addition to the aforementioned fossil groups, the occurrence of holoplanktic graptolites

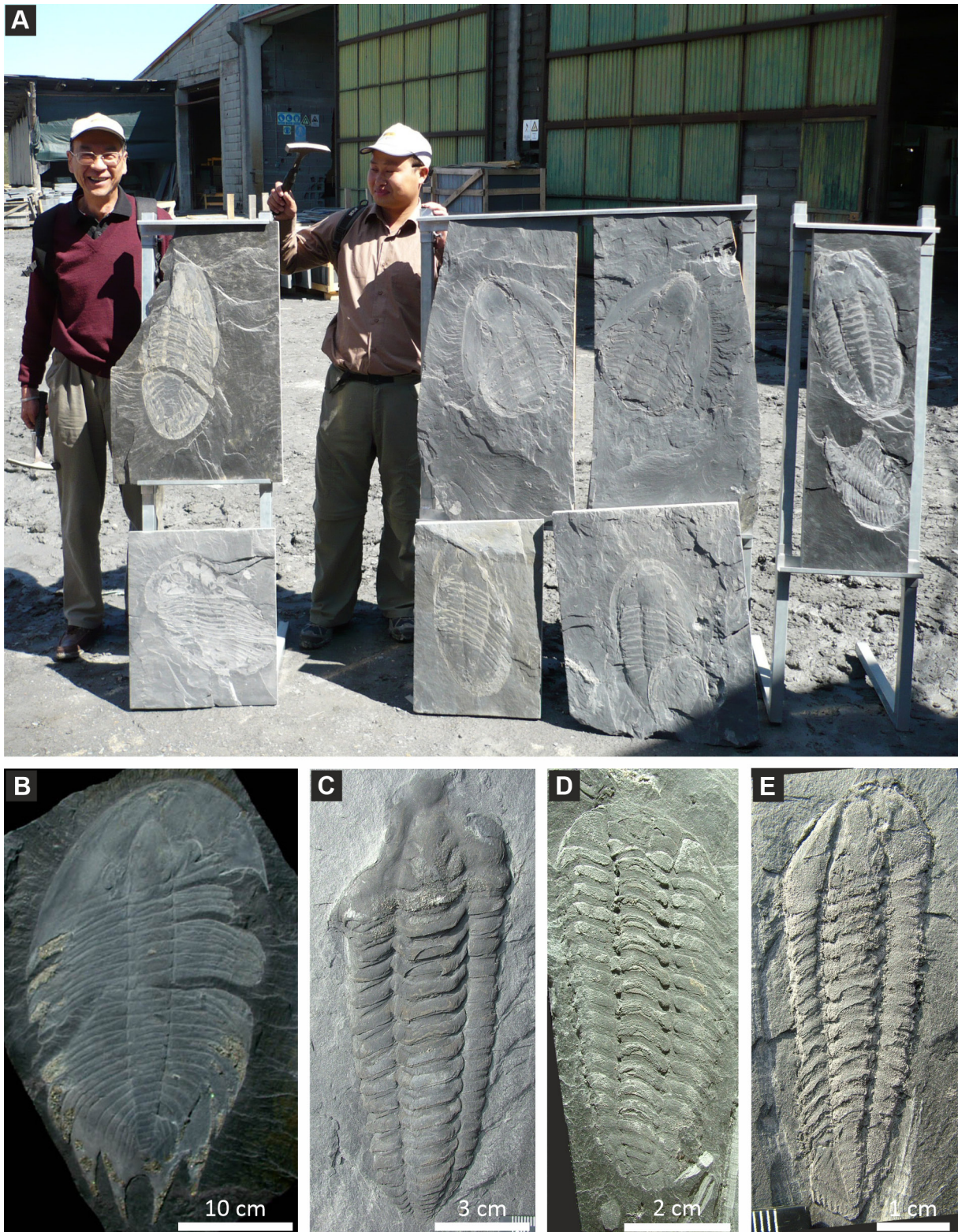


Figure 2. Some middle Darriwilian trilobites from the Canelas slate quarry. A) large specimens of *Ogyginus forteyi* Rábano on display next to the slate processing unit in June 2008, with the Chinese trilobitologist Zhi-Yi Zhou (to the left). B) *Hungioides bohemicus* (Novák in Perner). C) *Neseuretus avus* Hammann. D) *Placoparia cambriensis* Hicks. E) *Salterocoryphe lusitanica* (Thadeu). All the specimens were expanded tectonically by a primary cleavage (S_1) sub-parallel to bedding (S_0).

(*Didymograptus*, *Aulograptus*, *Acrograptus*, *Xiphograptus*?, *Glossograptus*) is more common as accumulations, in horizons where the bottom currents favored the concentration of their colonial remains on the seafloor. Although the Canelas quarry provides one of the most important places in the world to see giant trilobite fossils, and some features of their ecological and social behavior, its most emblematic giant species – *Ogyginus forteyi* and *Hungioides bohemicus* – are known in other localities of the Central Iberian Zone, for example, in the Spanish region of the Toledo Mountains (Figs. 1 and 3). However, therein they are quite rare, probably because the oxygen-depleted conditions that favored their opportunistic proliferation in Arouca did not prevail or did not exist at all. On the other hand, the large and consecutive fronts exploited in the Canelas quarry, as opposed to small holes dug by hand in other sectors where the

same stratigraphic levels occur, maybe biasing the data for a proper comparison.

A final observation refers to the famous ‘gigantism’ of many species from the Canelas quarry. If we compare the size of the specimens in Arouca to those of the same species in other comparable middle Darriwilian assemblages from the Toledo Mountains (Spain), it is striking that not only does the size of the trilobites exceed the normal dimensions of Spanish specimens, but the same happens to the adult specimens of many brachiopods, gastropods, bivalves and hyolithids, among others. Gutiérrez-Marco *et al.* (2007) argued that the giant trilobites of Canelas were affected by a cleavage parallel to bedding, which produced an increase in their dimensions. Later, Gutiérrez-Marco *et al.* (2009) estimated that tectonic deformation could have produced length increases by up to 15%. But these estimates are difficult to confirm because the

Figure 3. Some giant trilobites from the middle Darriwilian of the Toledo Mountains (central Spain), demonstrating the lateral stratigraphic continuity of the particular trilobite bed of the Valongo Formation more than 400 km eastwards –see Fig. 1. Above, a specimen of *Ogyginus forteyi* Rábano 40 cm long, slightly affected by diagenetic compaction, from the locality of Ventas con Peña Aguilera (province of Toledo). Below, an isolated glabella preserved in full relief, of a huge specimen of *Hungioides bohemicus* (Novák in Perner) from Navas de Estena (province of Ciudad Real). Specimens and pictures from Alejandro Navarro/Timoteo López and Museo Geominero (Madrid), respectively.



gerontic forms of trilobites are rare and difficult to characterize with certainty. On the contrary, when undeformed brachiopods and mollusc fossil shells from the Toledo Mountains are compared with the same flattened and deformed species from Canelas, it can be concluded that the latter (including associated trilobites from the same levels) show tectonic expansion coefficients close to 50%, which implies that about one-third of the current size of the fossils is due to deformation. For this reason, when we refer to the real size of any trilobite or other fossil from Canelas, it is most likely that we should discount up to 30% to better estimate the biological dimensions of their exoskeletons or shells. The role of deformation in the large dimensions of fossils in the Arouca region is undeniable, but it is difficult to estimate the actual size of the organisms that generated them. It is possible that, in addition to all other coincidences of preservation and deformation, there is also the fact that some trilobites, especially asaphids, have found ecological conditions there that allowed them to grow smoothly. Are the Arouca trilobite fossils among the largest in the world? Yes! Were the trilobites that generated them the largest that existed? We do not know yet...but in the end, size does not matter! The present considerations are only of a technical nature, since Canelas fossils will continue having a remarkably high scientific and educative interest, representing an outstanding and world-class palaeontological heritage.

Geotourism and Geotrail Potential

The Canelas Ordovician Geosite is one of the most relevant features of the Arouca UGGp geological heritage. Although the main quarry is not open to visitors, due to the risk of rock falls and landslides, as well as to avoid interference with the exploitation and machinery, the slate processing and industrial facilities are open to guided group visits in coordination with the adjacent CIGC. This private on-site museum plays a key role in the preservation and disclosure of this outstanding palaeontological heritage site, having been built to promote public outreach and scientific education, this is a

great example of effective public/private and civil society partnership (Goals 4, 8, 9, 11, 12, and 17 of the 2030 Agenda). The CIGC also offers a guided educational / pedagogical trail (the 'Palaeozoic Georoute'), an opportunity for a panoramic view of the quarry and the geological landscape around Canelas, going through the different Ordovician formations, also including a visit to a Roman gold mine located at the highest point in the area, where the Santa Justa Formation outcrops.

Apart from the quarry and its on-site museum, the Arouca UGGp incorporated this geosite in one of their 'Geosites Route' (Rocha 2016) and disseminates its paleontological heritage at national and international tourism fairs. Previously, the Canelas quarry and its trilobites were also included in the 'Route of the Stone', a CYTED-RUMYS project in the Ibero-American area (Sousa *et al.* 2012).

Finally, the public awareness of this geosite is always ensured by its integration in publications and in the educational programs of the Arouca UGGp, which promote activities in several of its educational centres, partially co-sponsored by the Arouca City Council. The broadcast of several TV programs nationwide on this geosite, and its appearance twice in the Portuguese edition of the *National Geographic* magazine (November 2001 and April 2013) have contributed largely to the fame of this important palaeontological locality. In addition to all these, other initiatives and examples related to popular culture have been developed. They included people dressing up as trilobites in the carnivals of the town; giant trilobite bronze sculptures in a roundabout; a restaurant named as 'Trilobite' and authentic trilobites decorating the inner walls of some other restaurants, whose dishes adopted names related to Ordovician fossils, trilobite-shaped pastries sold in some shops, and various craft products relating to these fossils.

In this context, it is relevant to mention that the existence of giant trilobites is assumed as an identity reference of the territory by both the political

power and the population, in equal circumstances with the Monastery of Arouca (national monument). Indeed, with the construction of the onsite museum and the creation of the geopark, the giant trilobites became part of the imagination of the local inhabitants and a reference for those who, from all over the country, visit the territory, which is now commonly known as ‘Arouca: land of giant trilobites’.

Conserving the Geosite

Among the various Ordovician geosites documented in the Arouca UGGp, the Canelas quarry stands out for its scientific relevance and for being an example of cooperation between industry, science and education (Sá *et al.* 2005; Sá & Gutiérrez-Marco 2006, 2008; Gutiérrez-Marco *et al.* 2006). Its outstanding geology and paleontology are well known among trilobite specialists and Palaeozoic geologists worldwide, having been officially visited, in a partnership with the CIGC, during the 4th International Trilobite Conference (Sá *et al.* 2008), the 11th International Symposium on the Ordovician System (Sá *et al.* 2011a), and in diverse field-trips organized in the frame of other international, Iberian or national meetings, such as the 14th Iberian Symposium of Geology Teaching (Valle Aguado *et al.* 2006), the 8th European Geoparks Conference (in September 2009), the 11th European Geoparks Conference (Sá *et al.* 2012a), the 1st International Geoscience Congress of Portuguese Speaking Countries (Sá *et al.* 2012b), or the 9th Portuguese Geological Congress (Sá *et al.* 2014), among others.

During the exploitation of the quarry, the most important fossils, either for their rarity or for their scientific value, are collected *in situ* with the help of machinery. Many others appear during the industrial processing of slates to reach the appropriate dimensions and thicknesses for commerce. The fossils are taken to the quarry warehouse, and after a scientific selection, they are integrated into the collection of the CIGC.

Although the ownership of the palaeontological collections of the CIGC remains in private hands, the formal partnership with the AGA – Arouca Geopark Association, the management structure of the Arouca UGGp, ensures the future availability of this palaeontological heritage for exhibitions, educational programs and collaboration with scientific research.

Finally, this outstanding geosite is already included in the National Inventory of Geological Heritage (Brilha & Pereira, 2011).

Summary

The Canelas slate quarry in the Arouca UGGp provided some of the world’s largest trilobite fossils. Study of large shells of other invertebrate groups (molluscs, brachiopods) co-occurring in the fossil assemblage shows that all of them are tectonically expanded, and that about one third of the current size of the fossils is due to deformation. This fact is caused by the development of a primary cleavage sub-parallel to bedding, which also increases the quality and mechanical properties of these roofing slates as a building material. However, Middle Ordovician trilobites like certain asaphid and dikelocephalids species, among which are the largest specimens of Canelas (up to 70 and 90 cm in length, respectively, after deformation), are known with their original dimensions in Spanish localities of the Toledo Mountains area and are also ‘gigantic’ trilobites. Gutiérrez-Marco *et al.* (2009) tentatively correlated the presence of these large trilobites on the Central Iberian shelf as possible evidence of polar gigantism, due to the palaeogeographic proximity of Iberia to the margin of Gondwana at that time, close to Ordovician South Pole. Although numerous ‘giant’ species, especially asaphid trilobites, are also recorded in the Lower Ordovician of Morocco, the existence of this ‘polar gigantism’ in the Ordovician is far from being unquestionably proven and further research is needed on this subject.

Nevertheless, the Canelas fossil site and the spe-

cial palaeoenvironmental conditions that gave rise to its formation, generated a window through which we can study the behavior of trilobites and other extinct groups of marine organisms 465 million years ago.

The record of this valuable paleontological heritage in the Arouca UGGp, and its implications for disseminating the history of life through such outstanding fossils as those of the Canelas quarry, contributed decisively to design a sustainable development strategy, essentially based on education and geotourism as one of the strategic axes of the Arouca UGGp (Rocha *et al.* 2010, 2014; Sá *et al.* 2012c).

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