Journal of Iberian Geology
https://doi.org/10.1007/s41513-024-00249-x

RESEARCH ARTICLE

Trilobite biostratigraphy of the Marianian (Cambrian Series 2) from Seville and Badajoz provinces (Zafra-Alanís Domain, Ossa-Morena Zone, Spain): a review

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Received: 10 November 2023 / Accepted: 4 July 2024

Abstract

The Cambrian outcrops within the Zafra-Alanís Domain, southwest Iberia contain the type localities of several trilobite genera, including *Alanisia*, *Saukianda*, *Perrector*, *Eops*, *Andalusiana*, *Protaldonia*, and nine trilobite species. These fossils are attributed to the Marianian regional Stage, spanning from the upper Stage 3 to the lower Stage 4 of Cambrian Series 2. Despite their significance, the biostratigraphy of these outcrops has remained understudied due to the scarcity of continuous stratigraphic sections and the lack of comprehensive biostratigraphic research in this region. In this work, we present a refined trilobite biostratigraphic framework by examining ten newly established stratigraphic sections bearing trilobite fossils of the Zafra-Alanís Domain, on the Northern flank of the Olivenza-Monesterio Antiform, spanning across the Badajoz and Seville provinces. This framework constitutes the foundation for future zonation of the Marianian Stage and contributes to a more precise understanding for international correlation. The Cambrian tectonosedimentary blocks of the Ossa-Morena Zone, formed due to the rifting process in southwestern Iberia during Cambrian times, extend into southwestern Spain and eastern Portugal. A revised delineation of these blocks has been carried out, including a new outline of the Feria Fault, now identified as the Guadalcanal-Assumar Fault. In addition, the stratigraphic and palaeontological analysis of the Cambrian outcrops in the Seville province (Sierra Morena de Sevilla Natural Park - UNESCO Global Geopark) allows their inclusion within the recently defined Viar-Benalija basin.

Keywords Lower Cambrian · Trilobite · Tectonosedimentary blocks · Ossa-Morena Zone · Biostratigraphy

Resumen

Los afloramientos del Dominio Zafra-Alanís, suroeste de Iberia, contienen las localidades tipo de varios géneros de trilobites: *Alanisia*, *Saukianda*, *Perrector*, *Eops*, *Andalusiana*, *Protaldonia*, y de nueve especies de trilobites. Estos fósiles son característicos del piso Marianiense, en la escala regional, que abarcaría desde la parte superior del Piso 3 hasta la inferior del Piso 4 de la Serie 2 del Cámbrico. A pesar de la importancia paleontológica de estos afloramientos, el estudio detallado de los mismos ha sido escaso, debido a la falta de secciones estratigráficas continuas y de un análisis bioestratigráfico exhaustivo en la región. En este trabajo se presenta una bioestratigrafía detallada, a partir de los datos de diez secciones con trilobites situadas en el Dominio de Zafra-Alanís, en el flanco norte del Antiforme de Olivenza-Monesterio, en las provincias de Badajoz y Sevilla. Este marco de trabajo es la base para el establecimiento de una detallada zonación con trilobites del Piso Marianiense que, además, contribuirá a una correlación internacional más precisa. Las cubetas

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Published online: 23 September 2024

tectonosedimentarias de la Zona de Ossa-Morena, formadas durante la etapa de *rifting* en el suroeste de Iberia durante el Cámbrico, se extienden por el suroeste de España y este de Portugal. Se revisan los límites de estas cubetas, destacando la delimitación más precisa de la falla de Feria, ahora identificada como la falla de Guadalcanal-Assumar. Además, el análisis estratigráfico y paleontológico de los afloramientos cámbricos de la provincia de Sevilla (Parque Natural Sierra Morena de Sevilla - Geoparque Global UNESCO), permite su inclusión dentro de la cubeta de Viar-Benalija, recientemente definida.

Palabras clave Cámbrico inferior · Trilobites · Cubetas tectonosedimentarias · Zona de Ossa-Morena · Bioestratigrafía

1 Introduction

The Cambrian Epoch 2 is exceptionally fossiliferous in southwestern Spain, where numerous sites with abundant lower Cambrian trilobites and other fossil groups have been found in the Sierra Morena region ('Montes Mariani' in Latin). This area has long been associated with the Marianian regional Stage, whose rocks and fossils have been studied over the last fifty years as part of the so-called 'Mediterranean Subprovince' (Sdzuy, 1972). The Marianian Stage encompasses the transition between Cambrian Stages 3 and 4, pending formal definition by the International Subconmission on Cambrian Stratigraphy (Zhang et al., 2017; Peng et al., 2020). However, although the FAD of the trilobite *Strenuella* is generally considered to mark the base of the Marianian, the stage has not been formally defined.

The catalogue of Marianian trilobites from the Ossa-Morena Zone (OMZ) comprises 23 genera and species, representing one of the highest-known records of trilobite diversity during Cambrian Series 2 in southern Europe. Some of these genera are also found in other regions like Portugal, France, the United Kingdom, Germany, Poland, Sweden, Russia, Morocco, the USA, Canada, China, Australia, and the northern and central parts of Spain. This distribution makes them a valuable tool for international correlation and palaeogeography (Perejón & Moreno-Eiris, 2006; Collantes et al., 2021a, b, 2022; Sepúlveda et al., 2022, in this volume). In addition, these trilobites have been key to enhancing our understanding of Cambrian rifting in the OMZ and reconstructing the palaeogeography of this region during the Cambrian Period, achieved through the differentiation and correlation of Cambrian sequences within the tectosedimentary blocks that exhibit alternating subsidence and uplift dynamics associated with Cambrian rifting (e.g., Liñán, 1984; Liñán & Quesada, 1990; Liñán & Gámez-Vintaned, 1993; Sánchez-García et al., 2003; Pereira et al., 2023).

Marianian trilobites have been known since the pioneering work by Delgado (1904), who reported a trilobite assemblage from Vila Boim (Elvas, eastern Portugal). In Sierra Morena (SW Spain), the first Marianian trilobites were briefly reported by Lotze (1939) from northern Huelva province, studied in detail by Richter and Richter (1941). Richter and Richter (1940) described a trilobite assemblage from northern Seville. Subsequently, these trilobite assemblages have been studied by several European palaeontologists, including Hupé (1953), Henningsmoen (1958), Sdzuy (1961, 1962), Gil Cid (1972, 1975, 1988), Liñán & Perejón (1981a), Liñán et al. (1997), Álvaro et al. (1998), Mayoral et al. (2021a, b), and Collantes et al. (2021a, b, 2022, 2024). Consequently, the Sierra Morena de Sevilla region stands out as the type location for nine Marianian trilobite species [*Alanisia guillermoi* (Richter & Richter, 1940), *Eops eo* Richter & Richter, 1940, *Saukianda andalusiae* Richter & Richter, 1940, *Strenuaeva sampelayoi* Richter & Richter, 1940, *Perrector perrectus* Richter & Richter, 1940, *Andalusiana cornuta* Sdzuy, 1961, *Protaldonaia morenica* Sdzuy, 1961, *Termierella sevillana* Sdzuy, 1961, and *Triangulaspis fusca* Sdzuy, 1962]. Other taxa described from the OMZ are *Delgadella* Walcott, 1912, *Delgadella souzai* (Delgado, 1904), *Callavia choffati* (Delgado, 1904), *Hicksia* Delgado, 1904 and *Hicksia elvensis* Delgado, 1904 from Vila Boim (Elvas, Portugal); and *Serrodiscus* Richter & Richter, 1941, *Calodiscus schucherti ibericus* Sdzuy, 1962, *Hicksia hispanica* (Richter & Richter, 1941), *Rinconia* Hupé, 1953, *Rinconia schneideri* (Richter & Richter, 1941), *Atops calanus* Richter & Richter, 1941, and *Chelediscus garzoni* Collantes et al., 2023 from northern Huelva province (Spain). Nevertheless, only four stratigraphical sections (Alconera 1, Alconera 3, Arroyo Galeón and Cerro del Hierro) were published with little representation of trilobites. The biostratigraphy of the mentioned sections as well as the other ten new sections from Seville (including Alanís, Constantina, Guadalcanal and Cerro del Hierro localities) and Badajoz (Llerena, Pallarés, and Alconera localities) are now studied (Fig. 1).

The objective of this research is to reassess the sites and sequences of Marianian trilobites situated within the Seville (Sierra Morena de Sevilla UNESCO Geopark) and Badajoz provinces, with the aim of refining Cambrian Stages 3–4 (Marianian) biostratigraphy and correlations across the OMZ and the broader region, and in future defining biozones that could be used to formally define the regional Marianian Stage.

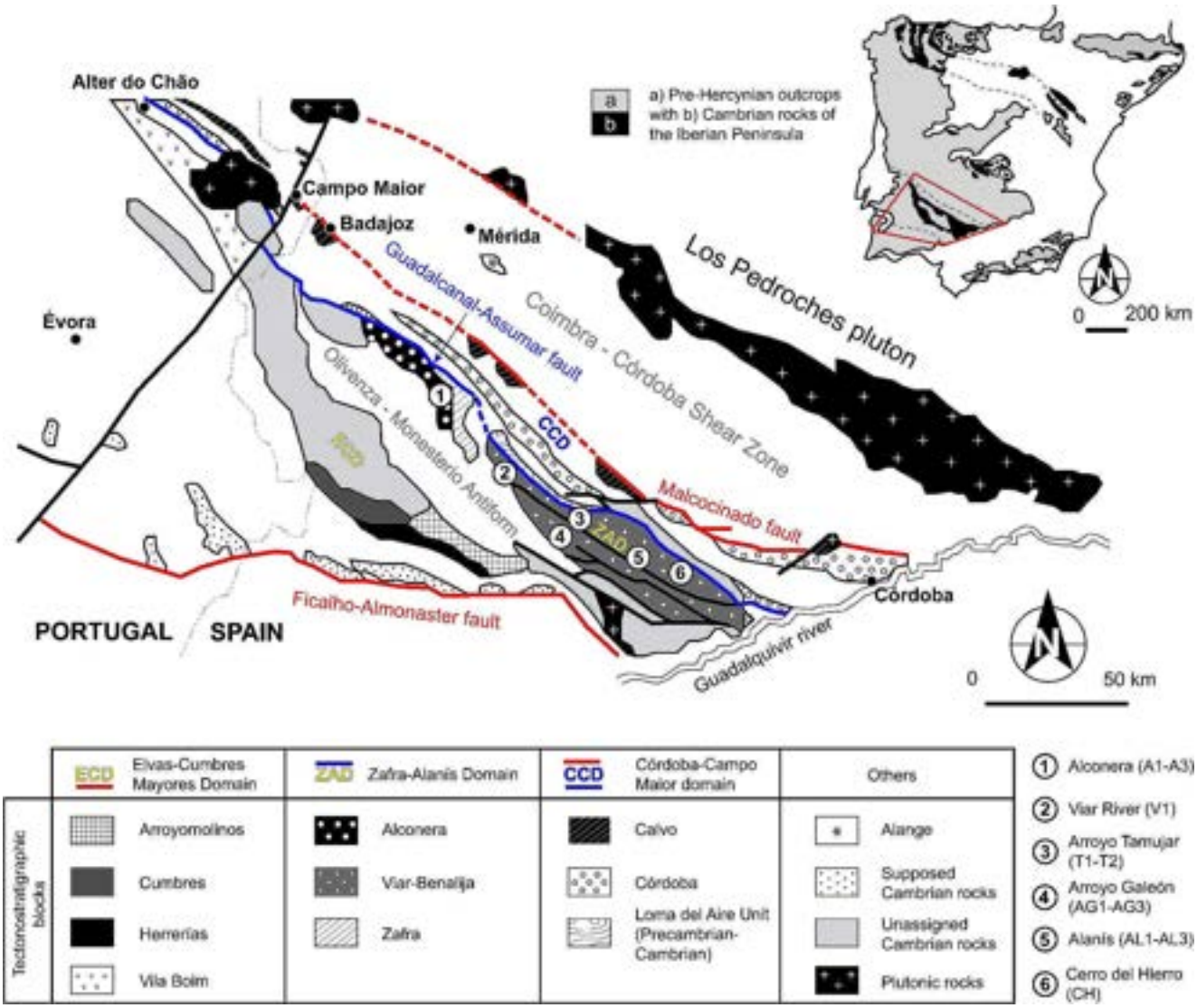

Fig. 1 The Guadalcanal-Assumar Fault and their relation with the Cambrian tectonostratigraphic blocks of the Ossa-Morena Zone. (modified from Liñán & Quesada, 1990). (1) to (6) geographic location of the studied sections

2 Geological framework

The study area is encompassed within the OMZ (Lotze, 1945), a tectonic segment of the Iberian Massif and one of the southernmost divisions of the European Variscan Orogen. This zone is characterized by distinctive stratigraphy and tectonic evolution (Quesada, 1990). It is bounded by two suture zones and is considered one of the terranes currently subject to debate regarding correlation and nature (Sánchez-García et al., 2016). The two suture zones are the Variscan Badajoz-Córdoba Shear Zone to the north and the Pulo do Lobo Zone to the south, limited by the Ficalho-Almonaster fault (Quesada, 2006). Other authors (e.g. Martínez Catalán, 2011) support that the Variscan South Iberian Shear Zone represents the southern boundary of the OMZ.

The Cambrian outcrops within the OMZ are divided into units commonly named as "cubetas" in Spanish (Liñán, 1984), referred to as blocks in the subsequent text, and defined as tectonostratigraphic blocks bounded by faults. These blocks display distinct facies and thickness variations due to the Cambrian rift margin (Liñán & Quesada, 1990; Sánchez García, 2001; Sánchez-García et al., 2003; Collantes et al., 2022). Nowadays, ten blocks have been identified in OMZ, and their chronological framework has been well established through trilobites (Delgado, 1904; Richter & Richter, 1940, 1941; Sdzuy, 1961, 1962; Liñán Guijarro, 1978; Liñán & Sdzuy, 1978; Liñán & Perejón, 1981a; Gozalo et al., 1994; Liñán et al., 1995, 2005, 2008; Álvaro et al., 1998; Collantes et al., 2021a, b, 2022, 2023, 2024), archaeocyaths (Perejón, 1973, 1975a, 1975b, 1975c, 1989, 1994; Moreno-Eiris, 1988, 1994; Menéndez et al., 1999;

Perejón et al., 1981, 2008), and acritarchs (Palacios et al., 2021). This information permits improved correlations and an in-depth understanding of the Cambrian rifting evolution of the Sierra Morena region.

Traditionally, the Cambrian formations in the Seville and Badajoz provinces have been included within the Córdoba-Alanís Domain (sensu Delgado Quesada et al., 1977; Liñán Guijarro, 1978), or the Zafra-Alanís-Córdoba Domain (Apalategui Isasa et al., 1983). However, a reevaluation of prior palaeontological, stratigraphical, and geological data suggests the presence of two distinct domains within the northern flank of the Olivenza-Monesterio: the Córdoba-Campo Maior Domain and the Zafra-Alanís Domain, separated by the Guadalcanal-Assumar Fault (Fig. 1). This tectonic boundary, initially referred to as the Feria Fault by Liñán and Perejón (1981a), extends from the Guadalquivir River near Palma del Río (Spain) to beyond Crato, in Portugal, tracing over the Assumar Fault and encompassing the Loma del Aire Unit (as defined by Garrote, 1976) in its central portion.

The newly identified Córdoba-Campo Maior Domain includes the Sierra de Córdoba and Cerro Calvo blocks, exhibiting similar stratigraphic formations. The primary distinction between these blocks lies in the differences in thickness, indicative of a rift sequence (Liñán & Quesada, 1990; Sánchez García, 2001; Sánchez-García et al., 2003). Rocks assigned to the Córdoba Block extend into Portugal through the Cambrian outcrops of Assumar-Campo Maior. In contrast, some outcrops belonging to the Cerro Calvo Block span from Casas de la Cierva (Spain) to Ouguela-Barro Bueno localities (Portugal) (Fig. 1). This extension of Spanish Cambrian blocks into Portugal follows the statements of Gonçalves (1971), Gonçalves et al. (1972, 1978), and Pereira and Silva (1999), and within the central region of the Badajoz-Córdoba Shear Zone (or Coimbra-Badajoz Shear Zone, sensu Pereira & Silva, 2002).

The Zafra-Alanís Domain (or Zafra-Alanís synclinorium sensu Alía, 1963) lies in the northern sector of the Olivenza-Monesterio Antiform. It encompasses the Alconera, Zafra, and Viar-Benalija blocks (Fig. 1). These blocks consist of NW-SE oriented outcrops due to the predominant orientation of the Guadacanal-Assumar Fault taking part of the sinistral strike-slip structure. The Loma del Aire Unit (Garrote, 1976) and its associated Cambrian sequence (Sánchez-García et al., 2016) are implicated in the central segment of this structure (Fig. 1). The Zafra-Alanís Domain is delimited to the north by the Guadalcanal-Assumar fault and to the south by the Olivenza-Monesterio Antiform. On the southern flank of the Olivenza-Monesterio Antiform, the Elvas-Cumbres Domain houses the Cambrian outcrops in Spain, extending into Portugal through the Alter do Chao-Elvas Sector (as described by Oliveira et al., 1991, Pereira & Silva, 2002) (Fig. 1).

Reasons supporting the extension of the Guadalcanal-Assumar Fault across the OMZ, and its palaeogeographic significance, rise from several factors: (1) the absence of the Armorican Quartzite Formation (Gutiérrez-Marco et al., 2002, p. 46) in the southern region, (2) the absence of Marianian trilobite facies in the northern domains (Córdoba-Campo Maior and Obejo-Valsequillo domains), (3) the different Cambrian trilobite deformation, which is almost absent in the northern domains and strongly pronounced in the southern ones, (4) the different configurations of the Cambrian blocks and the main geological structures, being subparallel to the north of the Guadalcanal-Assumar Fault and oblique to the south, (5) the increase of the number of tectonostratigraphic blocks in the southern domain with respect to the northern ones, and (6) the relative homogeneity in the Cambrian successions in the northern blocks reflected by a standard stratigraphic nomenclature and their heterogeneity in the southern ones, with each blocks having a different stratigraphic nomenclature depending on author (Figs. 1 and 2).

In conclusion, the Guadalcanal-Assumar Fault is bordered to the north by the Cambrian successions of the Córdoba-Campo Maior and Obejo-Valsequillo domains. In contrast, the Zafra-Alanís and Elvas-Cumbres domains lie to the south. Due to the similarities in stratigraphy, facies sequence, and the presence of common Ovetian trilobite genera and species (Pillola, 1993; Liñán et al., 2005), the Cambrian outcrops of the Cotentin Peninsula in the Armorican Massif (Doré, 1969, 1994; Pillola, 1993; Went, 2021) can be considered a natural extension of the domains situated to the north of the Guadalcanal-Assumar Fault, as proposed by Liñán and Gámez-Vintaned (1993: Fig. 7).

3 Trilobite sites and sections

The Zafra-Alanís Domain's trilobite sites are in the Viar-Benalija and Alconera blocks (see Fig. 1). The Zafra Block lacks any documented Cambrian trilobite facies. The Viar-Benalija Block is presently defined to encompass all the Cambrian fossil-bearing exposures in the Seville province as well as those in the eastern portion of the Badajoz province. The Alconera Block comprises the corresponding Cambrian outcrops in the western segment of the Badajoz province.

3.1 Viar-Benalija Block

The lower Cambrian sequence is characterised by the Torreárboles Formation, Campoallá series and Alanís beds in

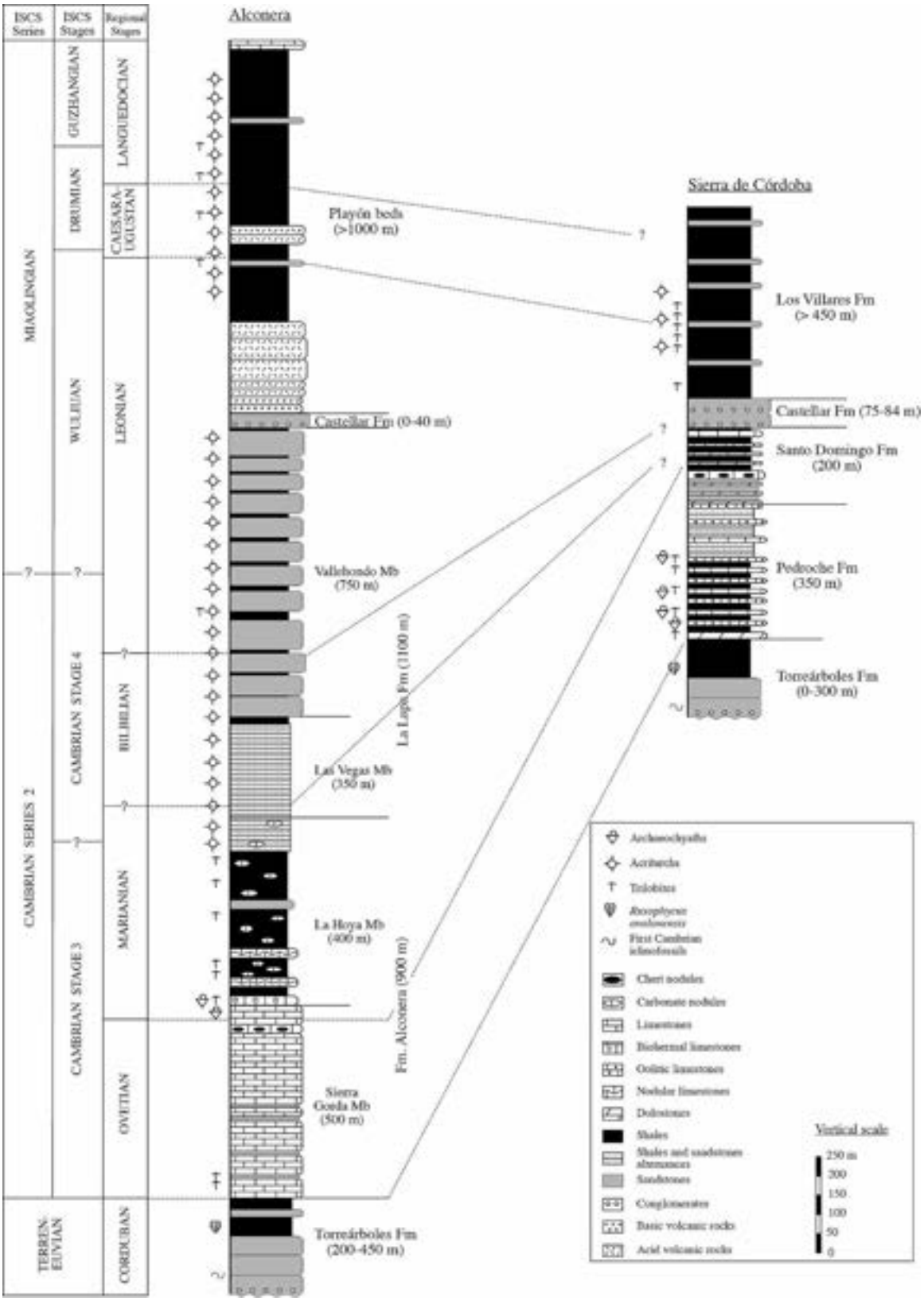

Fig. 2 The Sierra de Córdoba and Alconera block sequences show the main changes on either side of the Guadalcanal-Assumar Fault (modified from Liñán et al., 2008)

stratigraphic order (sensu Mayoral et al., 2021a, Fig. 3). From a historical perspective, Simon (1939) established a succession comprising the Tambor beds, Campoallá series, and Alanís beds in the southern region. In the northwestern area, however, the sequence comprised the Sotillo conglomerates, Valverde quartzites, Estebayanes beds, Agua limestone, and Benalija beds (Fricke, 1941, 1952). The Tambor beds and Sotillo conglomerates-Valverde quartzites were reassigned in the 1980s to the widespread Torreárboles Formation (e.g., Liñán & Perejón, 1981a; Liñán, 1984; Apalategui Isasa et al., 1983, 1990; Mayoral et al., 2004, 2005, 2008a, b, 2021a, b, c). Recent research indicates that the Estebayanes beds and Agua limestone are synonymous with the Campoallá beds. Similarly, the Benalija beds corresponds to a lateral change of facies of the Alanís beds (Mayoral et al., 2004, 2005, 2008a, b, 2021a, b; Collantes et al., 2022).

The biostratigraphy of this block is now supported by the trilobite successions in monoclinal sequences of Alanís, Arroyo Tamujar, Arroyo Galeón and Cerro del Hierro sections in Seville province and the Río Viar and Alconera sections in Badajoz province. All trilobite levels are found in the Alanís beds.

Alanís was one of the first Cambrian trilobite localities discovered in Sierra Morena (Simon, 1939), around the Alanís railway station on the Alanís-Cazalla de la Sierra road. The trilobites were collected from 13 different points ("Fundpunkte" or Fp.) without specific stratigraphic order around the 62 km point (now 57 km point) of this road. These trilobites were studied in detail by Richter and Richter (1940). According to these authors, it was impossible to identified the poorly material from Richters's Fp. 1, 3, 8, and 9. Specimens from Fp. 5, 7 h, 7i, and 7k were collected ex-situ. The Alanís material of Richter and Richter included species from the so-called *Saukianda*-Fauna (later

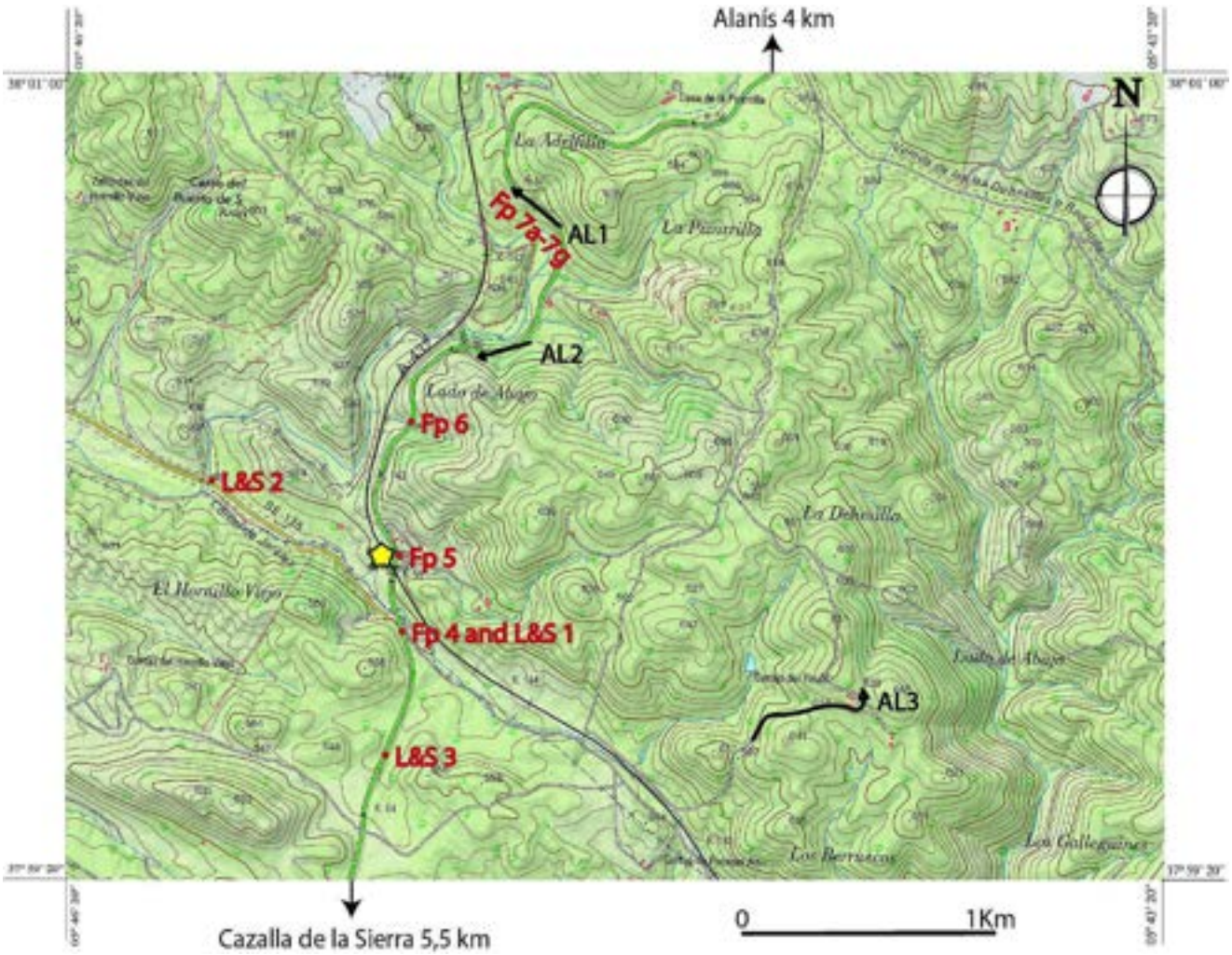

Fig. 3 Topographic map of the Alanís fossil site (number 5 in Fig. 1) with the location of the Richter and Richter (1940, Fp 4–6 and Fp 7a-7 g); Lotze (1961) and Sdzuy (1961) "Fundpunkts1-3": L&S1-3; and the AL1, AL2 and AL3 sections. Star: "Apeadero (train stop) de Alanís". Topography created with "Mapa a la Carta" of the Instituto Geográfico Nacional, http://www.cnig.es

"*Saukianda andalusiae* band" of Lotze, 1961). Our geological study of these points reveals that they are levels that are part of an anticlinal fold trending NE-SW (see Spanish Geological Map nº 899, Apalategui Isasa et al., 1983). We have now specified that the trilobite points 7a-7 g are situated on the northern flank in normal stratigraphic order, while the trilobite points 4–6 are on the SE flank in 6-5-4 stratigraphic order (Fig. 3).

Lotze (1961) and Sdzuy (1961) referred to three new trilobite points (Fp.1-Fp. 3) along the Alanís-Cazalla de la Sierra road and Cordel de Jarales path (Fig. 3) that were studied by Sdzuy (1961, 1962). The "Alanís Fp. 1" contains *Ellipsostrenua alanisana* Sdzuy, 1961(=*Strenuaeva sampelayoi* Richter & Richter, 1941, sensu Collantes et al., 2024), the "Alanís Fp. 2" has *Saukianda andalusiae* Richter & Richter, 1940 and the "Alanís Fp. 3" point has *Serrodiscus bellimarginatus* (Shaler & Foerste, 1888) and *Delgadella souzai* (Delgado, 1904). The Sdzuy's Alanís Fp. 1–2 may be assigned now to the middle Marianian and the Fp. 3 to the upper Marianian according to their trilobite assemblages.

Three sections are now studied in the Alanís locality (AL) from a biostratigraphic point of view: AL1, AL2 and AL3. The AL1 section (Fig. 4), with 17 levels in 110 m, is located on the northern flank of the Alanís railway station fold (Apalategui Isasa et al., 1983 from 38º 00' 31.56" N 5º 45' 05.05" W to 38º 00' 34.36" N 5º 45' 10.68" W), which encompasses the "Fundpunktes" 7a-7 g of Richter and Richter (1940) (see Fig. 4). Its trilobite content is similar to that cited by Richter and Richter (1940), with the addition of *Delgadella souzai* found in level 2. The AL2 section (from 38º 00' 16.98" N 5º 45' 06.75" W to 38º 00' 13.54" N 5º 45' 14.26" W) is located on the southern flank of the fold mentioned above, and it contains the same trilobite assemblage as the points 4–6 of Richter and Richter (1940). Finally, the new AL3 section (Fig. 4) is located at the dust road to Cortijo El Título (Fig. 3), east of the Alanís railway station (from 38º 00' 16.98" N 5º 45' 06.75" W to 38º 00' 13.54" N 5º 45' 14.26" W). It is located along the northern flank of a syncline fold trending NE-SW (see Spanish Geological Map nº 920, Angoloti Apolinario et al., 1975). Here, *Strenuella* sp. A is found in the lower part of the sequence with *Delgadella souzai* (Delgado, 1904), followed by the co-occurrence of *Eops eo* and *Saukianda andalusiae*. The last occurrence of *Delgadella souzai* is in line with the first occurrence of *Serrodiscus bellimarginatus* in the upper part of the sequence (Fig. 4).

The Arroyo Tamujar (T) and Arroyo del Molino sites around Guadalcanal (Seville) were initially documented by Lotze (1961), while the trilobite analysis was conducted by Sdzuy (1961, 1962) who distinguished "Guadalcanal Fp 1" and "Guadalcanal Fp 2" in the Arroyo Tamujar site, and called "Guadalcanal Fp 3" to the Arroyo del Molino site. Sdzuy's investigation led to the discovery of various trilobite species, including *Andalusiana cornuta* Sdzuy, 1961, *Termierella sevillana* Sdzuy, 1961, *Termierella* sp., and *Triangulaspis fusca* Sdzuy, 1962, all found in "Guadalcanal Fp. 1". Moreover, Sdzuy (1962) identified '*Serrodiscus speciosus silesius*' (=*Serrodiscus bellimarginatus* sensu Collantes et al., 2022) in "Guadalcanal Fp. 2", whereas in "Guadalcanal Fp. 3", the presence of *Strenuaeva sampelayoi*, *Saukianda andalusiae*, and *Alanisia guillermoi* was established. The Arroyo Tamujar site is the locus typus of *T. sevillana* and *Andalusiana cornuta*, as well as for the bradoriid *Hipponicharium hispanicum* Gozalo & Hinz-Schallreuter, 2002.

Two sections (T1, T2) are now studied in the Arroyo Tamujar (see Spanish Geological Map nº 899, Apalategui Isasa et al., 1983; from 38 03' 17.56" N 5º 50' 21.81" W to 38º 03' 18.05" N 5º 50' 23.10" W and from 38º 03' 17.10" N 5º 50' 21.69" W to 38º 03' 15.82" N 5º 50' 23.10" W, respectively). The T1 section (Fig. 5) is located at the Senda de Los Sayales, near the intersection with the Arroyo Tamujar to the southeast along the dust road. This section encompasses Sdzuy's (1962) Fp. 1 and Fp. 2, and three trilobite associations have now been identified. The first comprises *Andalusiana cornuta*, *Termierella sevillana*, *Protaldonaia morenica*, brachiopods, and hyoliths. The second comprises *Andalusiana cornuta* and *Triangulaspis fusca*. The third association is only represented by *Serrodiscus bellimarginatus*.

The T2 section (Fig. 5) encompasses the riverbed of the Arroyo Tamujar stream, going from its intersection with a dust road between the Guadalcanal-Cazalla de la Sierra localities (known as "Senda de los Sayales") to a point located 50 m downstream. It represents a sequence composed of fine sandstones, characterised by four fossil-bearing levels: the first level contains *Triangulaspis fusca* and brachiopods, the second *Andalusiana cornuta* and the third is composed of *Delgadella souzai*, *Protaldonaia morenica*, *A. cornuta* and *Termierella sevillana*. A fourth association consists of *A. cornuta* and *T. sevillana* (as depicted in Fig. 5). It should be noted that both *Delgadella souzai* and *Protaldonaia morenica* are now documented for the first time in the Arroyo Tamujar site. Through the biostratigraphic examination of the T1 and T2 sections, it has been concluded that the stratigraphic arrangement of Sdzuy's Guadalcanal "Fundpunktes" is as follows: Fp. 3, Fp. 1 and Fp. 2.

Three sections have been sampled at the Arroyo Galeón (AG) site (see Spanish Geological Map nº 898, Apalategui Isasa et al., 1990; from 38º 02' 01.88" N 5º 55' 08.06" W to 38º 01' 54.02" N 5º 55' 09.73" W; from 38º 01' 53.29" N 5º 55' 10.84" W to 38º 01' 52.83" N 5º 55' 11.99" W and from 38º 01' 50.96" N 5º 55' 17.37" W to 38º 01' 50.59" N 5º 55' 19.20" W). Liñán and Perejón (1981b) published

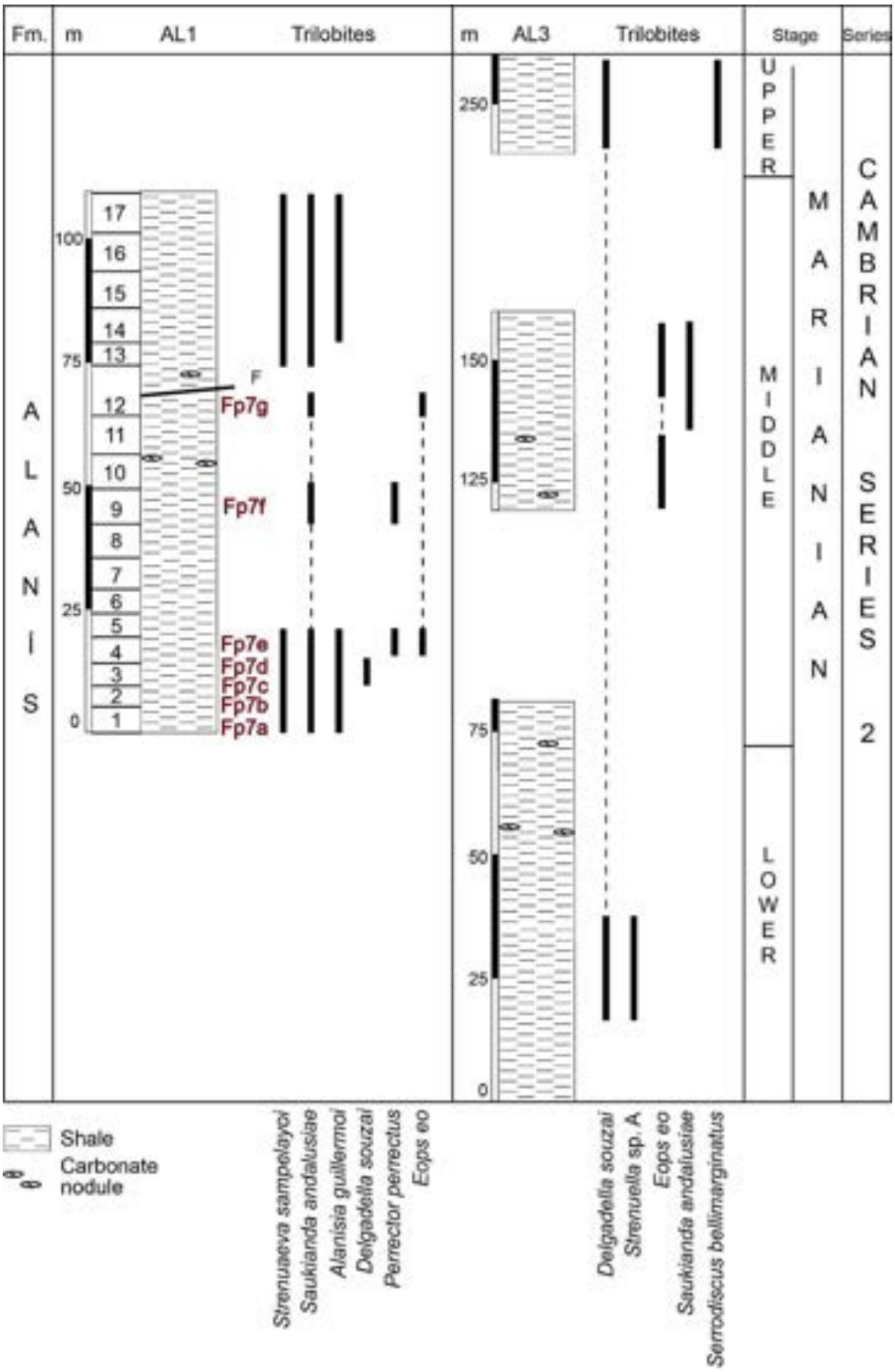

Fig. 4 Alanís 1 and 3 (AL1 and AL3) sections and their trilobite record, with indication of the presumable position of Fp7a-Fp7g from Richter and Richter (1940)

a composite section of this site where AG1 is just below of the AG2 and AG3 in a monoclinal sequence containing archaeocyaths of VIII-IX zones alternating with the trilobites *Pagetiellus* sp., *Strenuella* sp., *Alanisia* cf. *guillermoi*, *Saukianda* sp. and *Eops*? sp.

The AG1 section (Fig. 6) is situated on the right bank of the Benalija River, extending from the highway bridge located between the km 8 and 9 of the Cazalla de la Sierra-Guadalcanal road (SE-176) to the mouth of the Galeón stream. Within this section, two distinct trilobite associations have been identified: the lower association includes

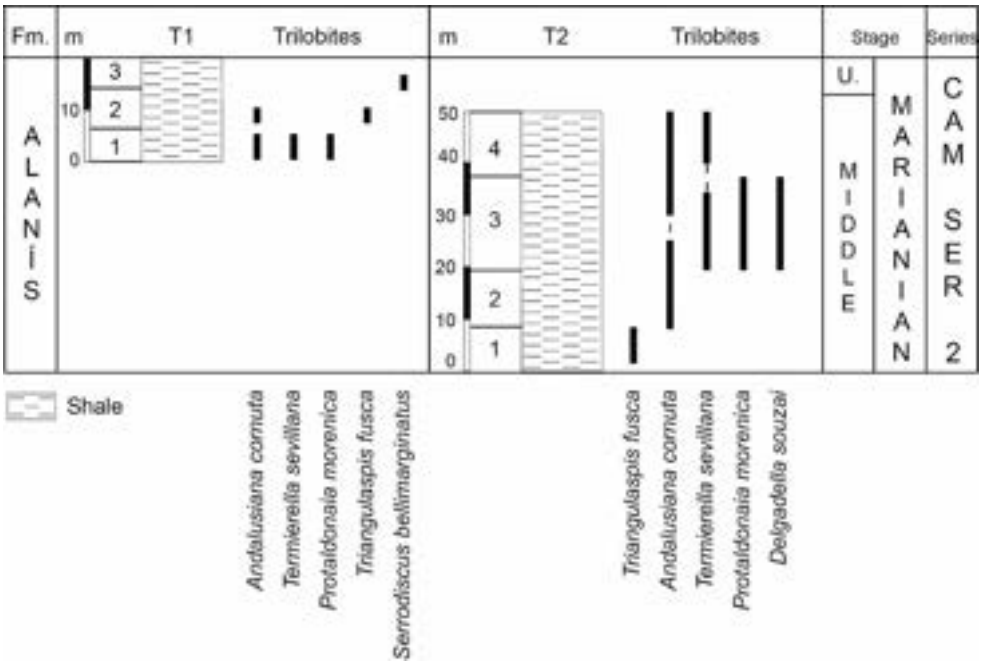

Fig. 5 Arroyo Tamujar 1 and 2 (T1-T2) sections and their trilobite record

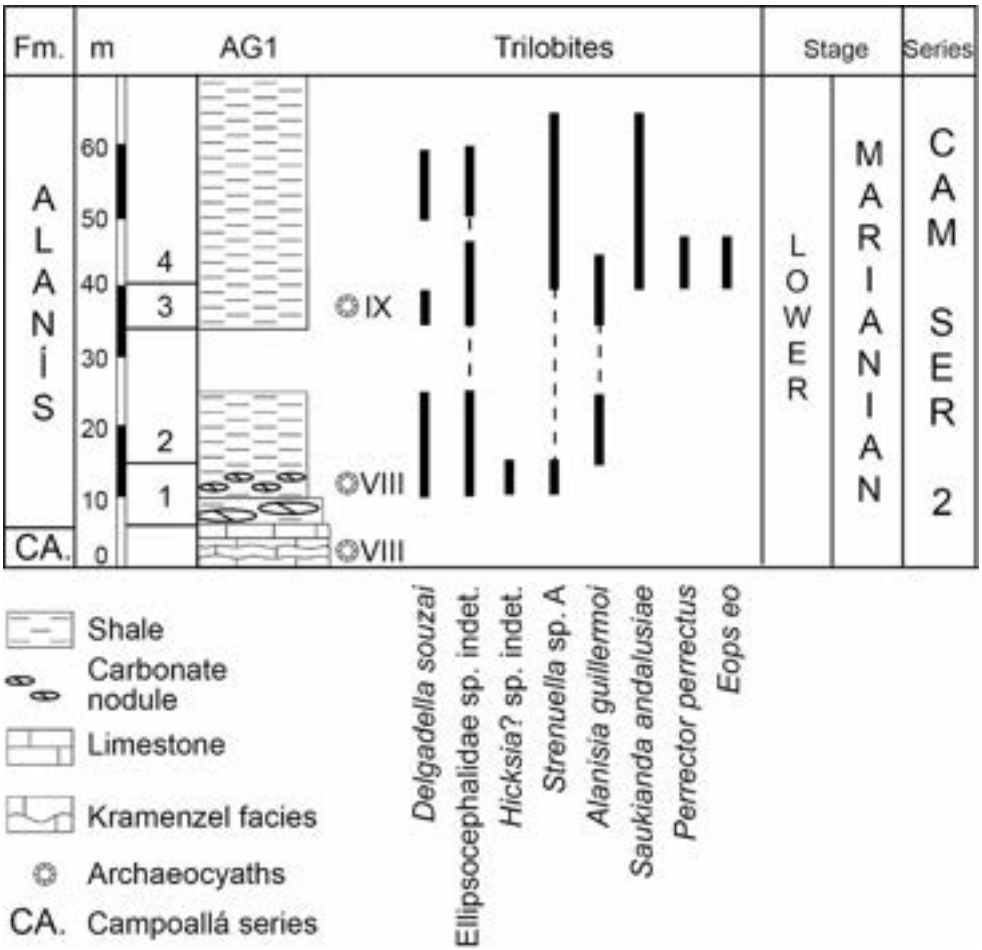

Fig. 6 Arroyo Galeón 1 (AG1) section and their trilobite record, with indication of the archaeocyaths levels (Liñán & Perejón, 1981b) and archaeocyaths zones (Perejón, 1994; Perejón & Moreno-Eiris, 2006)

species such as *Delgadella souzai*, *Strenuella* sp. A, *Hicksia*? sp. indet., *Alanisia guillermoi*, and an unidentified ellipsocephalid, together with archaeocyaths of the Zone VIII and IX (Perejón, 1994; Perejón & Moreno-Eiris, 2006). The second association comprises *D. souzai*, *Strenuella* sp. A, *Perrector perrectus*, *Eops eo*, *Alanisia guillermoi*, and another unidentified ellipsocephalid.

The AG2 and AG3 are situated downstream, from a fault on the same right bank of the Benalija River, in this monoclinal sequence (Fig. 7). The AG2 section has provided *D. souzai*, *Saukianda andalusiae*, *Strenuella* sp. A, and Ellipsocephalidae. A covered area follows this. In the AG3 section, two associations have been identified, the lower contains *D. souzai*, *P. perrectus*, and *E. eo;* and the upper has *Strenuaeva sampelayoi*.

The Cerro del Hierro (CH) site features a lower Cambrian sequence encompassing the Torreárboles Formation, Campoallá series, and Alanís beds. It has been interpreted that this region emerged during the late Ovetian due to the so-called Cerro del Hierro regression (Liñán & Gámez-Vintaned, 1993; Mayoral et al., 2021a), which led to the development of extensive karst on the Campoallá series buried by the Alanís beds. The latter is composed of shale, fine sandstone, and occasional levels of nodular limestone (referred to as the "Kramenzel" facies) (Miras & Rodríguez, 1990; Miras & Galán, 1992; Mayoral et al., 2021a). The lower Marianian trilobites, including *Saukianda andalusiae*, *Strenuella* sp. A., *Eops*? sp., *Delgadella souzai*, and *Acanthomimacca*? sp. were documented by Mayoral et al. (2008a, 2021a) and divided in two assemblages: the first consists of *Strenuella* sp. A and *Acanthomimacca*? sp. in the lower part, followed by the association of *D. souzai*, *Strenuella* sp. A, *S. andalusiae*, and *Eops* sp. (see Mayoral et al., 2021a, Fig. 4). This biostratigraphic sequence (from 37º 57' 09.71" N 5º 37' 19.29" W to 37º 57' 10.22" N 5º 37' 19.66" W) aligns with those found at the Alanís, Arroyo Tamujar, Arroyo Galeón, and Alconera sites, all of which are considered to be of early Marianian age.

The Río Viar (V) site (Fig. 8) is in southeastern Badajoz province (see Spanish Geological Map nº 898, Apalategui Isasa et al., 1990; from 38º 57' 08.32.71" N 6º 05' 48.90" W to 38º 08' 28.41" N 6º 05' 54.25" W). It was initially referred to by Lotze in 1961 as the Llerena-Pallarés road site, as well as the Llerena site by Sdzuy (1962), and it was studied by Sdzuy (1961,1962), Yochelson and Gil Cid (1984) and Gil Cid (1988). Sdzuy (1962) cited the assemblage of *Serrodiscus speciosus* (=*S. bellimarginatus* sensu Collantes et al., 2022) and it is the type locality of *Protaldonaia morenica* Sdzuy, 1961. A section has been studied on the Guadalcanal–Cazalla de la Sierra road, near its intersection with the Viar River, and it composed of shales with fine sandstone intercalations. Six trilobite levels (V1/1–6) have been identified: level 1 is composed of versicolor shales, which contain *S. bellimarginatus* and *Triangulaspis fusca*; levels 2 to 6 are composed of green shales, with a trilobite assemblage consisting of *S. bellimarginatus*, *Chelediscus garzoni* Collantes et al., 2023 and *Protaldonaia morenica*.

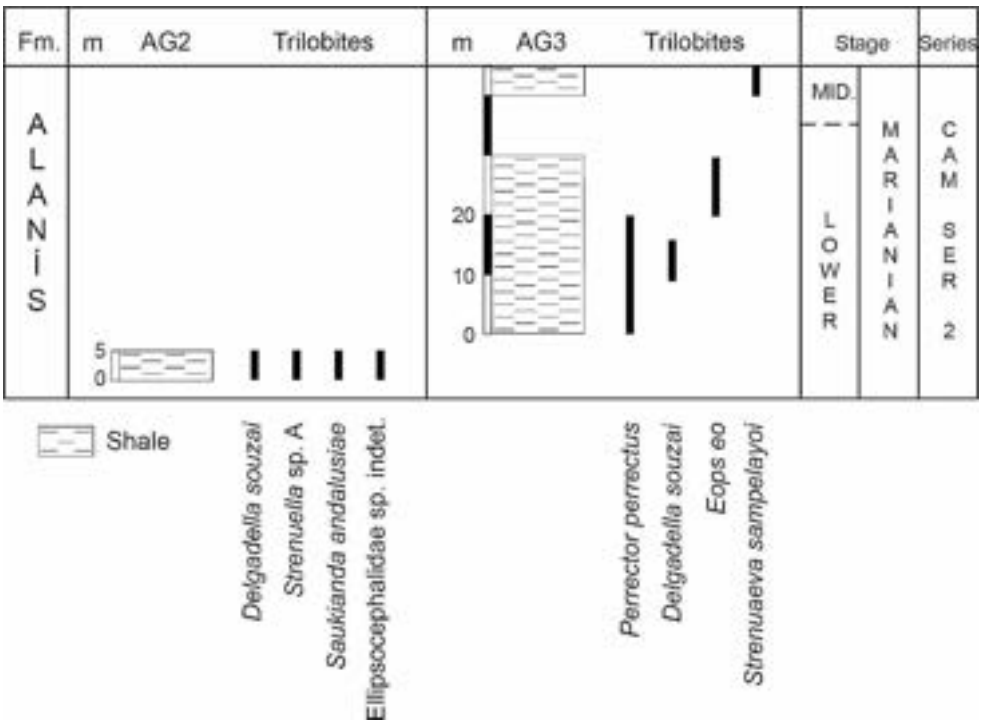

Fig. 7 Arroyo Galeón 2–3 (AG2-AG3) sections and their trilobite record

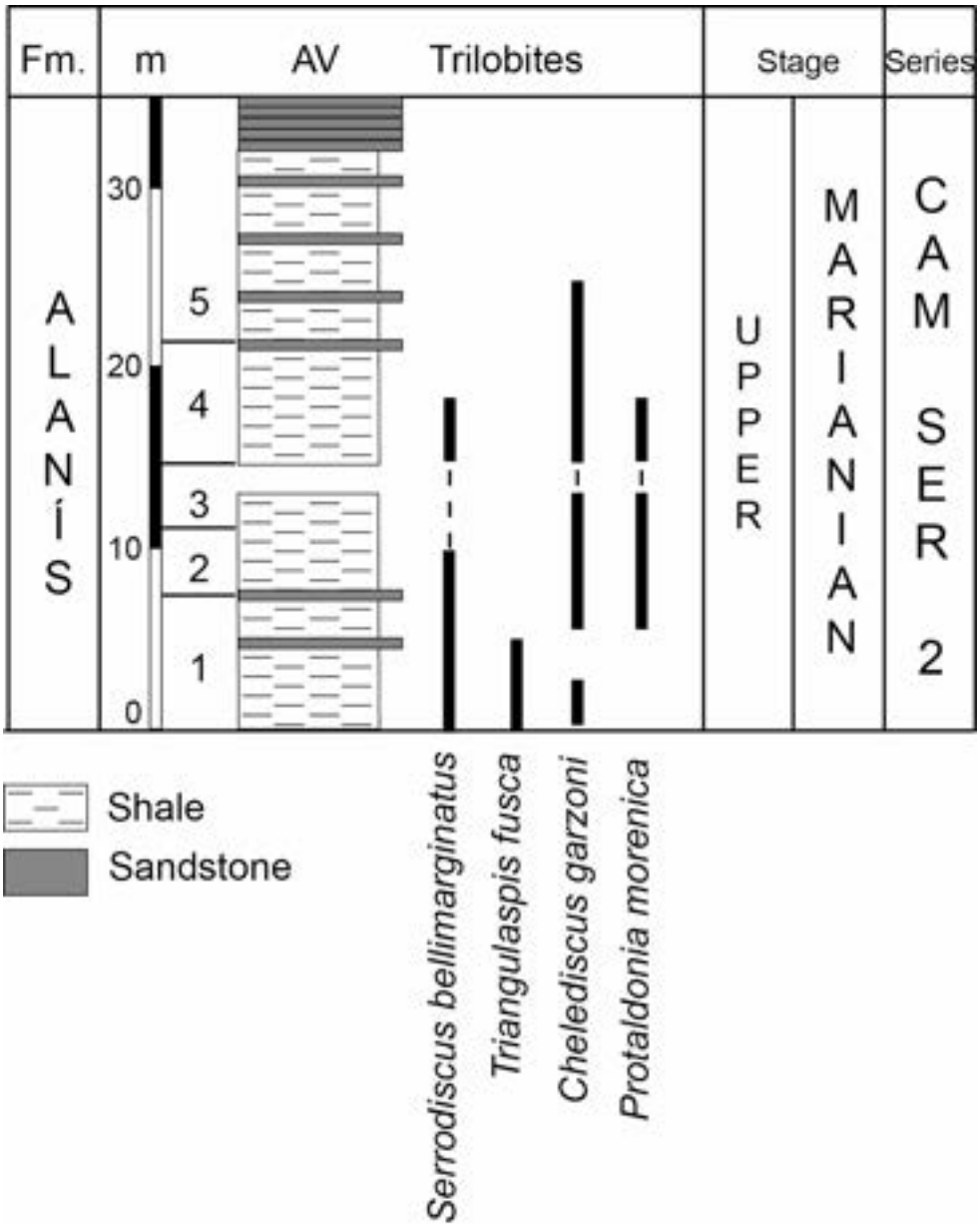

Fig. 8 Arroyo Viar (AV) section and their trilobite record

3.2 Alconera block

Liñán and Perejón (1981a) identified this unit as a tectonosedimentary block, redefining the previous stratigraphic nomenclature, and also studied the well-preserved and continuous section situated to the east of Alconera village (Vegas, 1971). Furthermore, they formally established the Cambrian sequence by integrating the Alconera Formation (comprising Sierra Gorda and La Hoya members) and the La Lapa Formation (consisting of Vallehondo, Las Vegas, and Castellar members) in their stratigraphic order. The age of these formations has been based on trilobite, archaeocyath and acritarch content, as documented by Liñán & Perejón (1981a), Liñán et al. (2002, 2004, 2008); Perejón and Moreno-Eiris (2006); Palacios et al. (2021). Later, Liñán et al. (1995) raised the Castellar Member to the status of the Castellar Formation (Fig. 2).

In recent years, Palacios et al. (2013) and Palacios et al. (2021) have presented two new proposals for stratigraphic nomenclature for this geological block. In the latter work, the authors conducted a comprehensive stratigraphical and palaeontological study of a new section with acritarchs located west of the Alconera village (Fig. 2).

In this study, we follow the stratigraphic nomenclature established by Liñán and Perejón (1981a; Fig. 2). The Marianian biostratigraphy of this geological block has been reevaluated using trilobite specimens found in the Alconera 1 (A1), Alconera 2 (A2), and Alconera 3 (A3) stratigraphic

sections, all of them detailed in Vegas (1971) and Liñán and Perejón (1981a). The Alconera 1 and Alconera 3 sections, both known for their abundance of archaeocyaths, trilobites, and brachiopods (Liñán & Perejón, 1981a: fig. 4), have been designated as the composite reference sections for this regional stage within the OMZ (Liñán et al., 1993), and their trilobite species content has been studied here for the first time (Fig. 9).

The sampling of the 49 layers in the A1 section (see Liñán & Perejón, 1981a, fig. 4; from 38º 22' 50.73" N 6º 29' 14.31" W to 38º 22' 47.99" N 6º 28' 46.63" W) allows us to distinguish two trilobite assemblages: the lower consists of *Strenuella* sp. A, *Delgadella souzai*, *Saukianda andalusiae*, *Eops eo*, and *Alanisia guillermoi*. The upper assemblage comprises *Strenuaeva sampelayoi*, *Strenuella* sp. A, *S. andalusiae*, *E. eo*, and *Gigantopygus* sp. (Fig. 9). Additionally, *Perrector perrectus* is found together with *S. andalusiae* and *Gigantopygus* sp. and has been incorporated into the upper assemblage. The A1 section is assigned to the lower-middle Marianian stage based on its trilobite content. The occurrence of both *Strenuella* sp. A and *Strenuaeva sampelayoi* in the same stratigraphic level are shared with other sections, indicating the lowermost part of the middle Marianian time. The comparative small thickness (15 m) of the shales with lower Marianian trilobites is also congruent with the previous record of archaeocyaths limestones (Zone VIII) in this section and reinforce the assignation of the *Strenuella*, *Delgadella souzai* and Zone VIII FADs to the base of this stage as occurs in the Arroyo Galeón (Perejón, 1986; Liñán et al., 1993; Perejón & Moreno-Eiris, 2006).

The A2 section is poorly exposed. It extends from the Alconera marble quarries to Zafra city (Badajoz), running parallel to the path to the east of the Fregenal de la Sierra-Zafra highway (from 38º 22' 41.31" N 6º 28' 46.45" W to 38º 22' 43.98" N 6º 28' 33.47" W). Within the La Hoya Member, three fossiliferous levels have been identified. The first assemblage consists of *Strenuella* sp. A and *Delgadella souzai* in level 1. This level comprises green shales overlying "kramenzel" limestones with archaeocyaths from Zone VIII (sensu Perejón, 1986). *Delgadella souzai* is also found in level 41 within purple shales, while *Serrodiscus bellimarginatus* is present in level 42, located immediately below the first outcrops of rhyolitic porphyries.

The A3 section is located in the eastern outskirts of Alconera, from the foothill of Sierra Gorda to the beginning of the so-called "Camino Colorado" dust road (Liñán & Perejón, 1981a: Fig. 2; from 38º 24' 07.26" N 6º 28' 42.11" W to 38º 24' 25.54" N 6º 27' 50.05" W). Twelve trilobite levels have

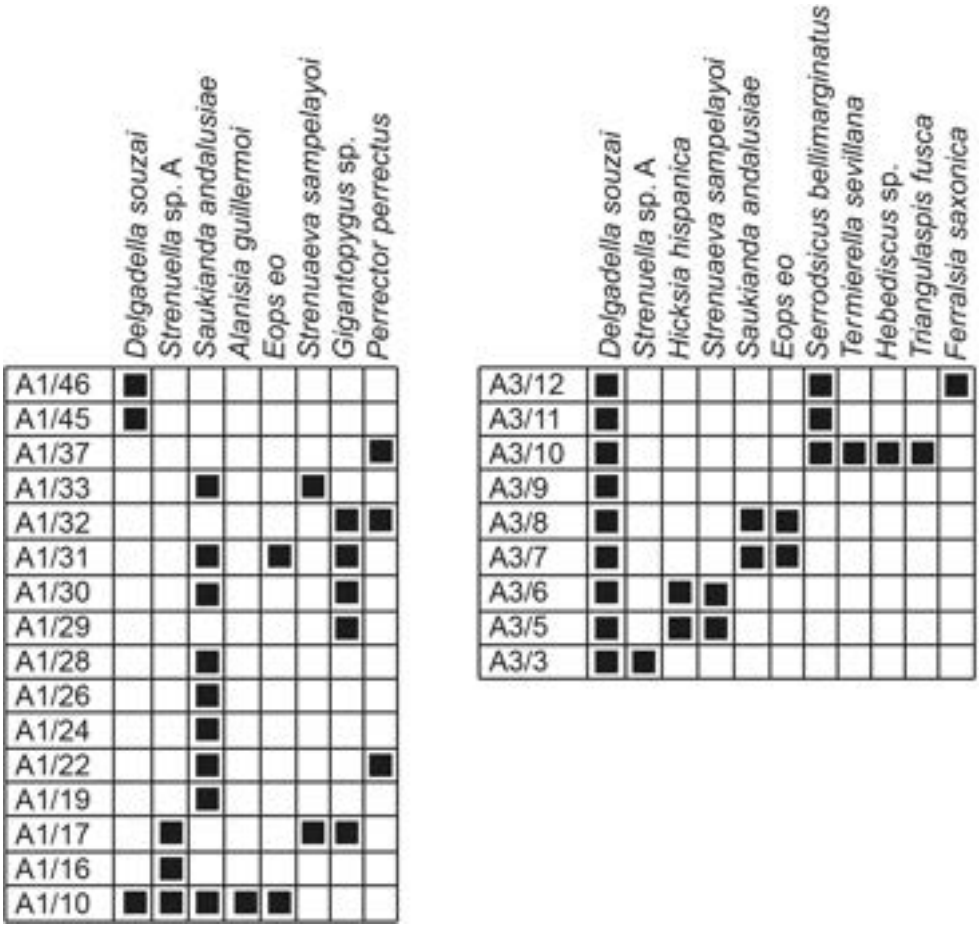

Fig. 9 Trilobite species newly identified in levels of the Alconera 1 and 3 sections, the levels had been referred to the A1 and A3 log from Liñán & Perejón (1981a: fig. 4)

been recognised in the La Hoya Member (see Liñán & Perejón, 1981a, fig. 5) belonging to the lower, middle and upper Marianian. In this section, the lower Marianian is characterized by *Strenuella* sp. A and *Delgadella souzai*; the middle Marianian by *Strenuaeva sampelayoi*, *Hicksia hispanica*, *Saukianda andalusiae*, *Eops eo* and *Delgadella souzai*; and the upper Marianian by *Serrodiscus bellimarginatus*, *Delgadella souzai*, *Triangulaspis fusca*, *Termierella sevillana* and *Hebediscus* sp., which is followed by the *Serrodiscus bellimarginatus-Ferralsia saxonica* level (Fig. 9).

4 Marianian trilobite biostratigraphy and correlation

The initial proposal for Cambrian biostratigraphy in the Ossa-Morena Zone was carried out by Lotze (1961), who identified 32 trilobite bands for the Spanish Cambrian based on their tentative position within a general stratigraphic scheme. The bands 4 to 12 are currently assigned to the Marianian times. Lately, Sdzuy (1971) subdivided the Spanish lower Cambrian into three regional stages: Ovetian, Marianian and Bilbilian.

However, subsequent research highlighted the limitations of this band-based model (as noted in Liñán & Quesada, 1990) and supported the division of the Marianian regional stage into lower, middle, and upper substages (Liñán, 1984; Liñán et al., 1993). This subdivision was defined by specific trilobite First Appearance Datums (FADs): *Strenuella*, *Strenuaeva*, and *Serrodiscus* marked the boundaries of the lower, middle, and upper Marianian substages, respectively (Liñán & Gámez Vintaned 1993, fig. 2).

Regarding the trilobite biostratigraphy, the initial trilobite records of the Zafra-Alanís Domain occur during the transgressive episode of the lower Marianian (Liñán & Gámez Vintaned 1993). The First Appearance Datum (FAD) of *Strenuella* precedes that of *Delgadella* in the Cerro del Hierro section, while the FADs of *Strenuella* and *Delgadella souzai* coincide in the Arroyo Galeón 1, Alconera1 and Alconera 3 sections. This should be interpreted in the context of OMZ rifting, where the record of endemic trilobites could precedes that of the more cosmopolitan miomers in those areas characterized by a more gradual subsidence and/or a later connection with open sea (Liñán, 1984; Liñán & Gámez Vintaned 1993).

A revised characterisation of the Marianian substages is now provided according to the new biostratigraphy studies from Alanís 1–3, Arroyo Tamujar 1–2, Arroyo Galeón 1–3, Cerro del Hierro, Río Viar and Alconera 1–3 sections from the Zafra-Alanís Domain. The lower Marianian is characterized by the assemblage of *Strenuella* sp. A, *Delgadella souzai*, *Acanthomicmacca*? sp., *Saukianda andalusiae*, *Alanisia guillermoi*, *Perrector perrectus*, and *Eops eo*. The middle Marianian strata contain *Strenuaeva sampelayoi*, *D. souzai*, *S. andalusiae*, *A. guillermoi*, *P. perrectus*, *E. eo*, *Termierella sevillana*, *Andalusiana cornuta*, *Triangulaspis fusca*, *Protaldonaia morenica*, *Hicksia hispanica* and *Gigantopygus* sp.; being the LAD of *Strenuella* sp. A locally coincident with the FAD of *Strenuaeva sampelayoi* in the lowermost middle Marianian. Finally, the upper Marianian is characterized by *Serrodiscus bellimarginatus*, *Termierella sevillana*, *Chelediscus garzoni*, *Triangulaspis fusca*, *Ferralsia saxonica*, *Protaldonaia morenica* and *Hebediscus* sp.; being the LAD of *Delgadella souzai* locally recorded in the lowermost part of the upper Marianian (Fig. 9). A biostratigraphic scheme depicting the distribution of trilobite species (Fig. 10), archaeocyaths and acritarchs zones, along with the Cambrian Stage 3 and Series 2, is presented in Fig. 11.

The correlation of the different Marianian sequences of the Iberian Peninsula is reassessed based on the new trilobite data. Lower Marianian trilobites are present in the lower part of the Alanís beds in the Viar-Benalija block (Cerro del Hierro and Arroyo Galeón 1–3; Liñán & Perejón, 1981b; Mayoral et al., 2008a, 2021a, herein) and the La Hoya Member (Alconera 1–3) in the Alconera block (Liñán & Perejón, 1981a, herein). Its presence is unknown in other areas of the Iberian Peninsula.

Middle Marianian trilobites are recorded in the Alanís beds (Alanís 1–3, Arroyo Tamujar1-2 and Arroyo Galeón 3; Richter & Richter, 1940, herein) and Alconera Formation of the Zafra-Alanís Domain (Liñán & Perejón, 1981a), as well as in the Herrerías shale (Sierra del Bujo), the Cumbres beds (Cumbres de San Bartolomé and Cumbres Mayores) and the Vila Boim Formation (Elvas, Portugal) of the Elvas-Cumbres Domain (Collantes et al., 2021b, 2024) in the OMZ. They are also present in the Endrinal Formation (Salamanca, Central Iberian Zone) with the occurrence of *Gigantopygus* (Rodríguez Alonso et al., 1995). Finally, the Ribota Formation of the Iberian Chains shows an important middle Marianian trilobite assemblage, with *Strenuaeva incondita*, *Lusatiops ribotanus*, *Kingaspis velata*, *Termierella* cf. *sevillana*, *Termierella* sp. and *Onaraspis garciae* (Sdzuy, 1961; Gámez et al., 1991; Liñán et al., 1996; Sepúlveda et al., 2021, 2022; Gámez Vintaned et al., 2023). It should also be noted that trilobites (*Lusatiops ribotanus*, *Strenuaeva incondita*, and T*ermierella* cf. *sevillana*) and acritarchs of the *Skiagia ciliosa* Zone are recorded together

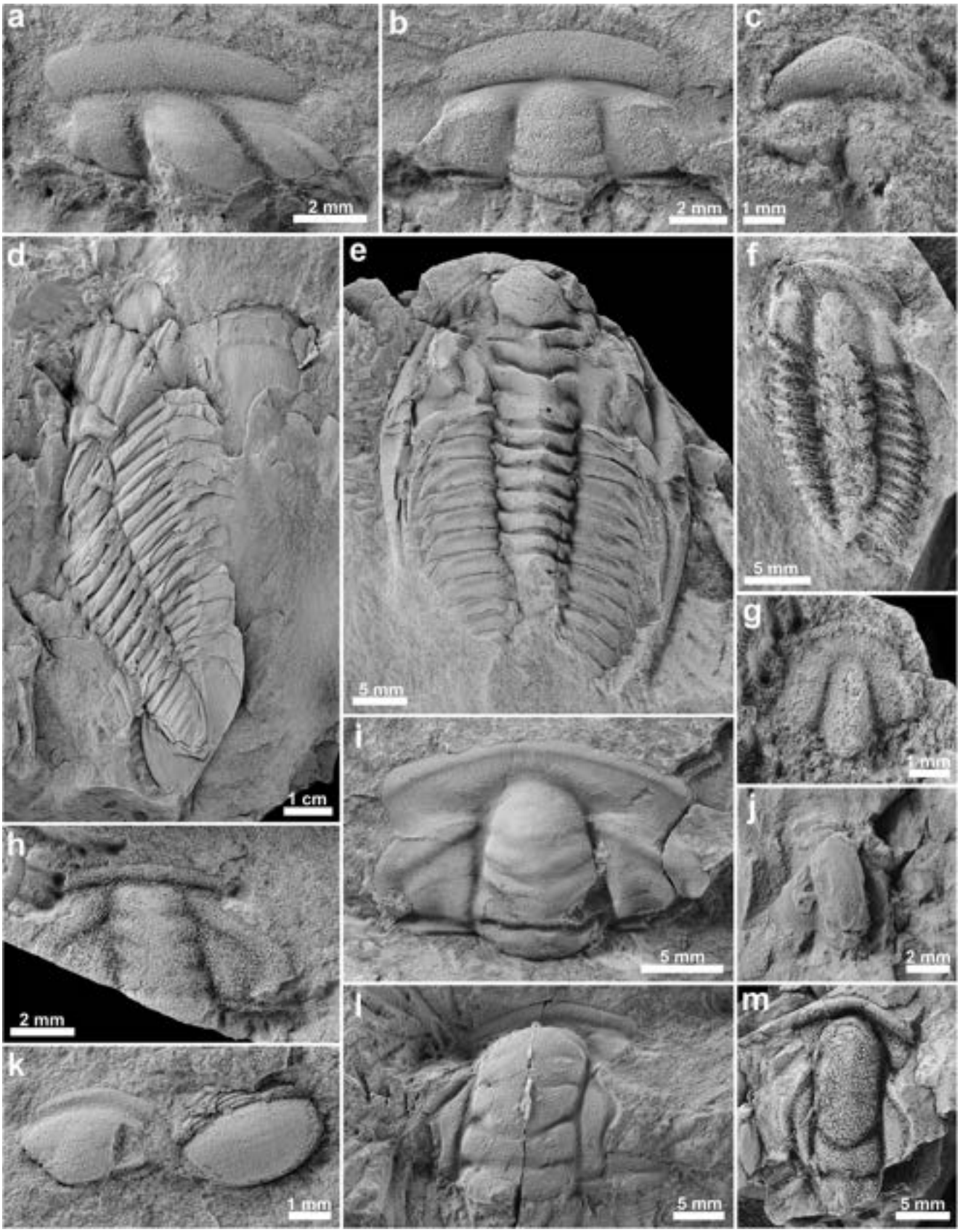
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Fig. 10 Selected Marianian trilobites from Zafra-Alanís Domain. (**a**,**b**) *Strenuella* sp. A, Alanís 3 (MPZ 2023/272) and Arroyo Galeón 1 (MPZ 2023/273) sections, respectively; (**c**) *Triangulaspis fusca* Sdzuy, 1962, Arroyo Tamujar 2 (MPZ 2023/274); (**d**) *Eops eo* Richter & Richter, 1940, Alanís 3 (MPZ 2023/275); (**e**) *Andalusiana cornuta* Sdzuy, 1961, Arroyo Tamujar 2 (MPZ 2023/276); (**f**,**g**) *Alanisia guillermoi* (Richter & Richter, 1940), Arroyo Galeón 1 (MPZ 2023/277) and Alconera 1 (MPZ 2023/278), respectively; (**h**) *Perrector perrectus* Richter & Richter, 1940, Arroyo Galeón 3 (MPZ 2023/279); (**i**) *Termierella sevillana* Sdzuy, 1961, Alconera 3 (MPZ 2023/280); (**j**) *Hicksia*? sp. indet., Arroyo Galeón 1 (MPZ 2023/281); (**k**) *Delgadella souzai* (Delgado, 1904), Alanís 3 (MPZ 2023/282); (**l**, **m**) *Saukianda andalusiae* Richter & Richter, 1940, Alconera 1 (MPZ 2023/283) and Arroyo Galeón 1 (MPZ 2023/284), respectively

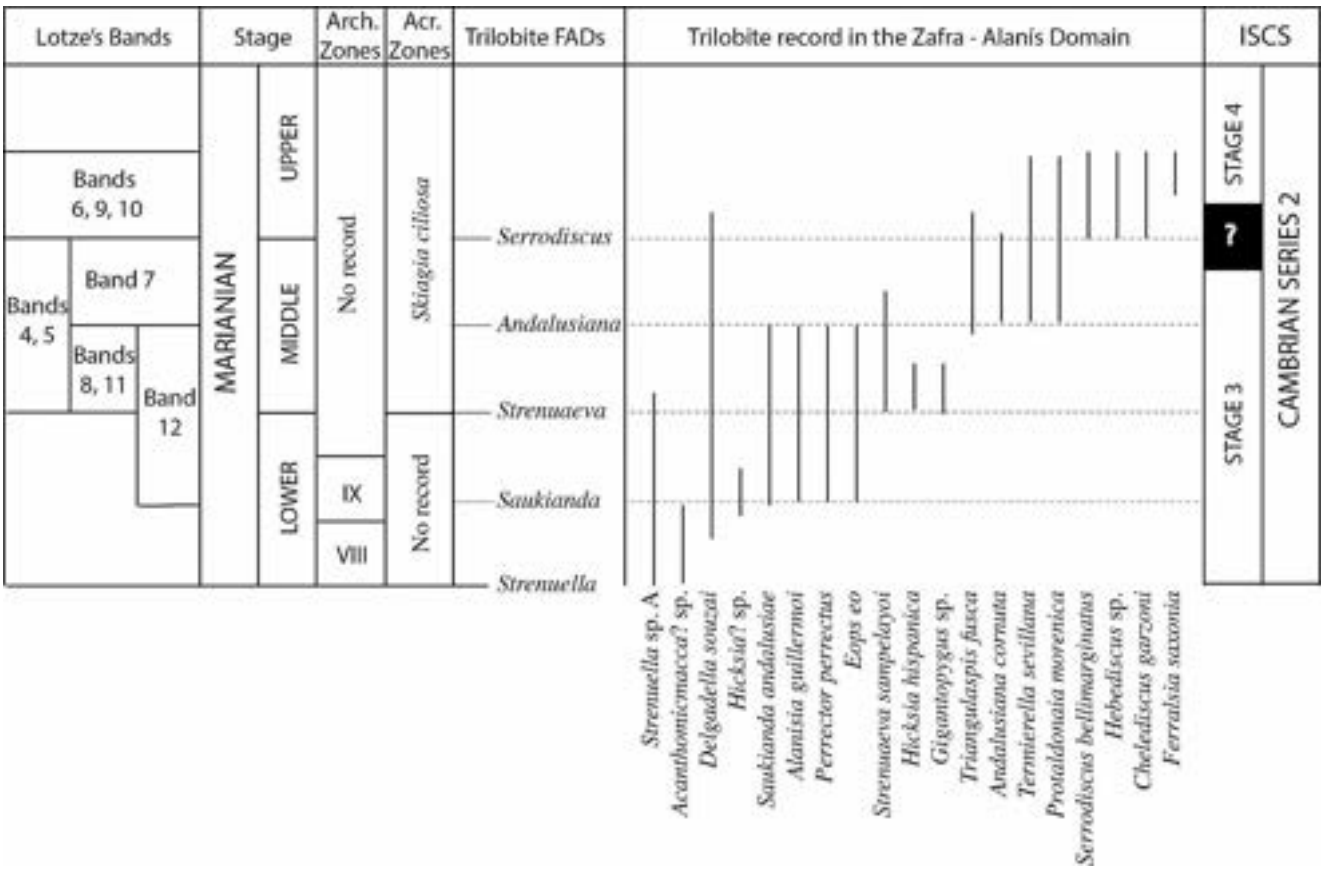

Fig. 11 Chart of the Marianian trilobites distribution of the Zafra-Alanís Domain. Lotze's Band after Lotze (1961); regional stages after Sdzuy (1971) and Liñán et al. (1993); Archaeocyath zones after Perejón (1986) and Perejón & Moreno-Eiris (2006), Acritarch zones after Palacios & Moczydlowska (1998) and Palacios et al. (2021); Trilobite FADs after Gozalo et al. (2003); Chronostratigraphic unit after de ISCS (Peng et al., 2020)

in the Borobia locality (Gámez et al., 1991; Palacios & Moczydlowska, 1998; Gámez Vintaned et al., 2023).

Upper Marianian trilobites in the OMZ occur in the lower part of the upper Marianian stage in both the Elvas-Cumbres Mayores (Collantes et al., 2021a, 2022, 2023; herein) and Zafra-Alanís domains (Liñán & Perejón, 1981a, herein). The trilobitic facies of the lower upper Marianian are also present in the base of the Huérmeda Formation in the Iberian Chains with *Strenuaeva incondita*, *Lusatiops ribotanus*, *Kingaspis velata*, *Kingaspis* cf. *velata*, *Paulaspis tiergaensis*, *Luciaspis matiasi*, *Onaraspis garciae*, *Acanthomicmacca* (*A.*) aff. *coloi*, *Andalusiana* cf. *cornuta*, *Redlichia isuelaensis*, *Triangulaspis* sp. and *Hebediscus*? sp. (Sdzuy, 1961; Liñán et al., 1993, 1996; Álvaro et al., 2019; Sepúlveda et al., 2021, 2022). One of the most complete upper Marianian sequences with trilobites is located at the Toledo Mountains (Central Iberian Zone; see Sepúlveda et al., in press).

5 Conclusions

The former Córdoba-Alanís Domain, including Córdoba, Seville, and Badajoz provinces, has now been divided in two domains: the Córdoba-Campo Maior and Zafra-Alanís Domains. These domains are separated by the Guadalcanal-Assumar Fault, which extends from the Guadalquivir Basin (Spain) to Crato (Portugal).

The blocks located to the north of the Guadalcanal-Assumar Fault share similar Cambrian sequences and

trilobite facies, whereas the southern blocks exhibit distinct Cambrian sequences and trilobite facies due to differential rifting dynamics on the OMZ during the Cambrian Period.

Ten new Marianian stratigraphic sections with trilobite species have been studied from Seville and Badajoz provinces. The trilobite assemblages of the different Marianian substages have been updated, enabling enhanced characterization and reaffirmation of the stratigraphic order of the proposed FADs of their boundaries. The trilobite diversity of the Marianian sequences of Seville and Badajoz provinces represents one of the most complete successions of Cambrian Series 2 of southern Europe.

Acknowledgements This work is a tribute to Dr Teodoro Palacios for his work in the study of the Precambrian and Cambrian of the Iberian Peninsula. He also regularly collaborated with us in the MAGNA Project (IGME) sampling many of the localities studied here. We thank Sören Jensen (Extremadura University, UNEX) for inviting us to participate in the tribute to Teodoro Palacios in Badajoz and for improving the original manuscript as well as to James Holmes (Uppsala University) and two anonymous referees. Thanks to Isabel Pérez Urresti, who assisted us with fossil photography. In 1982, EL and Teodoro Palacios (TP) visited the Cambrian outcrops in Alentejo to sample their respective successions, with assistance of Francisco Gonçalves from the University of Évora. EL and TP took part in the teams on the sheets 898-Puebla de Maestre (Apalategui Isasa et al. 1990) and 899-Guadalcanal (Apalategui Isasa et al. 1983) in 1980 and 1983, respectively. In 1996, EL, TP and RG explored the Cambrian sections of the OMZ in Portugal, receiving geological guidance from Manuel Francisco Pereira and Luis Lopes of the Évora University, to whom we are grateful. The present work has been carried out with financial help from Junta de Andalucía to the RNM 276 Research Group and the Centro Científico-Tecnológico de Huelva (CCTH). LC is supported by Portuguese fund by Fundação para a Ciência e a Tecnologia (Portugal) in the frame of the UI/DB/151298/2021 project. The cited and depicted trilobite material is held in the Museo de Ciencias Naturales of the Zaragoza University (MPZ 2023/272–284; MPZ 2022/770–799; MPZ2022/817–830 and MPZ 2022/840–859).

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

Declarations

Competing interests The authors declare no competing interests.

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