

63rd ANNUAL MEETING OF THE
PALAEONTOLOGICAL ASSOCIATION
2019 - VALENCIA, SPAIN
FIELD-TRIPS BOOK

PALASS 2019: FIELD-TRIPS BOOK



THE PALAEONTOLOGICAL ASSOCIATION
VALENCIA 2019



Editors: Samuel Zamora
Isabel Rábano



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Instituto Geológico y Minero de España
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Palaeozoic fossils from the Iberian Chains.

Back cover:

Panoramic view of Cabo de Huertas section and cenozoic invertebrate fossils from Alicante.

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PREFACE

The Palaeontological Association is one of the world's leading palaeontological societies, founded in 1957 with the aim of promoting the study of palaeontology and its allied sciences through publication of original research and field guides, holding regular meetings and field excursions; and funding a programme of annual grants and awards.

This year the Palaeontological Association celebrates its 63rd Annual Meeting in the city of Valencia in Spain, representing the first time this meeting has been organized in this country. As Chair of the organizing committee I would like to thank the Council members of the Association for offering us the opportunity to host such an important meeting for the palaeontological community.

The scientific sessions of the meeting are sandwiched by two field-trips, which I herein present in the mode of a publication in *Cuadernos del Museo Geominero*, edited by Samuel Zamora and Isabel Rábano, both from the Spanish Geological Survey (IGME, Instituto Geológico y Minero de España). The pre-conference field excursion will take place in one of the most famous areas with Palaeozoic rocks and abundant fossils in Spain, the Iberian Chain, located in the north-eastern part of the Iberian Peninsula. During the three-day excursion participants will review fossil invertebrate and vertebrate communities from the Cambrian through to the Devonian, and how they change according to intrinsic and extrinsic factors. The post-conference field-trip is a one-day excursion to the Miocene and Pliocene of the province of Alicante. During the day participants will visit several outcrops around Cabo Huertas, assigned to a Tortonian and Tyrrhenian age, where both open platform and coastal deposits have been described; followed by the spectacular coral reef of Santa Pola.

As Chair of the organizing committee of the 63rd PalAss Annual Meeting, I would like to thank the editors and leaders of the field excursions for their support and investment in the meeting. I would like to expand my acknowledgements to all participants, as well as those institutions that have provided financial support for the publication of this volume including both the Spanish Geological Survey and Generalitat Valenciana.

Dr Carlos Martínez-Pérez
Chair of the 63rd PalAss Annual Meeting, Valencia 2019
University of Valencia

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**PRE-CONFERENCE FIELD TRIP:
PALAEOZOIC FOSSIL ASSEMBLAGES FROM THE IBERIAN CHAINS
(NORTHEAST SPAIN)**

FIELD TRIP:

PALAEOZOIC FOSSIL ASSEMBLAGES FROM THE IBERIAN CHAINS (NORTHEAST SPAIN)

Samuel Zamora¹ (coord.)

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Keywords: Cambrian, Ordovician, Silurian, Devonian, invertebrates, vertebrates, environments, evolution.

INTRODUCTION

Samuel Zamora

Spain contains some of the most extensive and fossiliferous Palaeozoic outcrops in Europe, including invertebrate and vertebrate faunas that are internationally significant in terms of systematics, palaeoecology and palaeobiogeography. This field trip will review some of the most remarkable Palaeozoic localities from the Iberian Chains (Northeast, Spain). These are two large Palaeozoic outcrops (Western and Eastern Iberian Chains) trending NW-SE, separated by the Tertiary Calatayud-Teruel basin and considered the central part of the Iberian Cordillera. In this region, Palaeozoic rocks are structured into three tectonostratigraphic units separated by important faults (Jarque and Datos faults); from southwest to northeast they are named the Badules, Mesones and Herrera units (Lotze, 1929; Gozalo and Liñán, 1988; Álvaro *et al.*, 2018)

(Fig. 1). The Badules unit is the most extensive of the three units and crops in both the Eastern and Western Iberian Chains, showing a stratigraphic succession ranging from the Ediacaran to the Lower Ordovician. The Mesones unit contains rocks from the Ediacaran to the Miaolingian. Finally, the Herrera unit shows the most complete of the three successions with rocks ranging from the Furongian to the Permian. Palaeozoic fossils from the Iberian Chains are rich in the three units and the field trip will provide a complete view of fossil marine assemblages from the Cambrian Series 2 to the Devonian. Both, the Badules and Herrera units will be visited during the field trip.

During the first day of the field trip, we will visit the Herrera unit in the surroundings of Fombuena and Luesma, located in the Eastern Iberian Chains. Colmenar *et al.* (this guide) have provided an itinerary reviewing important new and classic localities preserving invertebrate communities from the Ordovician to the Silurian, which combines data from previous field excursions (Villas *et al.*, 2011, 2018; Zamora *et al.*, 2015), plus updated information. The Upper Ordovician faunas from the Fombuena and Cystoid Limestone formations have been described in several systematic papers (Chauvel *et al.*, 1975; Villas, 1985; Hammann, 1992; Gutiérrez Marco *et al.*, 1996; Jiménez-Sánchez, 2009, 2010; Cole *et al.*, 2017 among others), and are associated with a dramatic change in global climate (the so-called Boda Event). These strata record the immigration of marine invertebrates against the backdrop of global warming. This will be followed with a visit to the Silurian Badenian Formation represented by a low-diversity faunas of brachiopods, cephalopods, trilobites, molluscs and echinoderms.

The second day Zamora *et al.* (this guide) will introduce the Cambrian locality of Purujosa (Zaragoza), one of the most complete and interesting section in NE Spain. Large-scale excavations between the years 2005 and 2015 have provided an extensive collection of trilobites, echinoderms and other shelly fossils from the Miaolingian Mansilla and Murero formations, and also the first Guzhangian trilobites from the Iberian Chains (Álvaro *et al.*, 2013). This material is remarkable and includes some of the oldest representatives of major echinoderm clades (Zamora, 2010), including the oldest cinctan (Rahman and Zamora, 2009), cothurnocystid stylophorans (Zamora, 2010) and isorophid edrioasteroids (Zamora and Smith, 2010), as well as taxa that fill important gaps in echinoderm evolution, such as the most primitive bilateral echinoderms (Zamora *et al.*, 2012) and arm-bearing “pelmatozoans” (Zamora and Smith, 2012). In terms of the trilobites, the Purujosa assemblage has provided important collections of enrolled trilobites that demonstrated this behaviour was well established in the Cambrian (Esteve *et al.*, 2011; 2013), and also evidences of sublethal predation among paradoxid trilobites (Zamora *et al.*, 2011; Pates *et al.*, 2018). These evidences taken together will provide critical data on predator-prey interactions in the Cambrian. During the evening we will do a short visit to the classic Murero locality with one stop in the “Rambla de Valdemedes”. Murero is known since 1862 when De Verneuil discovered the “primordial fauna” (Anonymous, 1862). Since then Murero has been visited and excavated by numerous scientists and main palaeontological monographies on the trilobites were written by Sdzuy (1961) and Liñán and Gozalo (1986). In 1986 Conway-Morris and Robison (1986) reported a palaeoscolecid soft-bodied fossil from Murero and large excavations developed by Liñán and collaborators in the subsequent decades tried to demonstrate the importance of Murero preserving soft-bodied fossils. The aim of the evening will consist on visiting some of the classic sites that were excavated for such purpose.

The third day Valenzuela-Ríos *et al.*, (this guide) will cover important Devonian localities, mainly focused on the Nogueras and Mariposas formations (Lochkovian to lower Emsian), representing shallow-water marine environments with abundant invertebrate and vertebrate faunas. We will start visiting the classic locality of Las Viñas section, close to Santa Cruz de Nogueras village, showing the rich invertebrate fauna (brachiopods, echinoderms and trilobites) through the whole Nogueras Fm. and the transition to the Mariposas Fm. During the evening we will visit the south Barranco de Santo Domingo locality, within the

Nogueras Fm, with abundant corals, brachiopods, bryozoans and conodonts, highlighting the presence of interesting remains of vertebrates and plants, visiting the type locality of *Teruelia diezii*, an early polysporangio-phyte (Cascales-Miñana and Gerienne, 2017) and where a semiarticulated specimen of *Leonodus carlsi* (the earliest tooth-bearing shark) was discovered (Mader, 1986).

We hope that this field trip will exemplify how fossil communities changed during time from the Cambrian to the Devonian in a discrete area of Gondwana. This responds to evolutionary events (extinctions/appearance of groups) that are also observed in other regions, with the combination of local factors such as those driven by the geological record in the area.

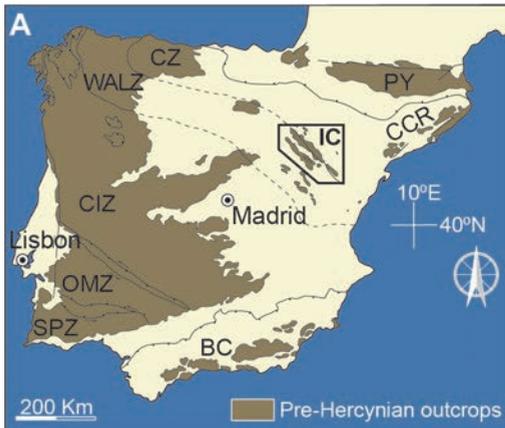
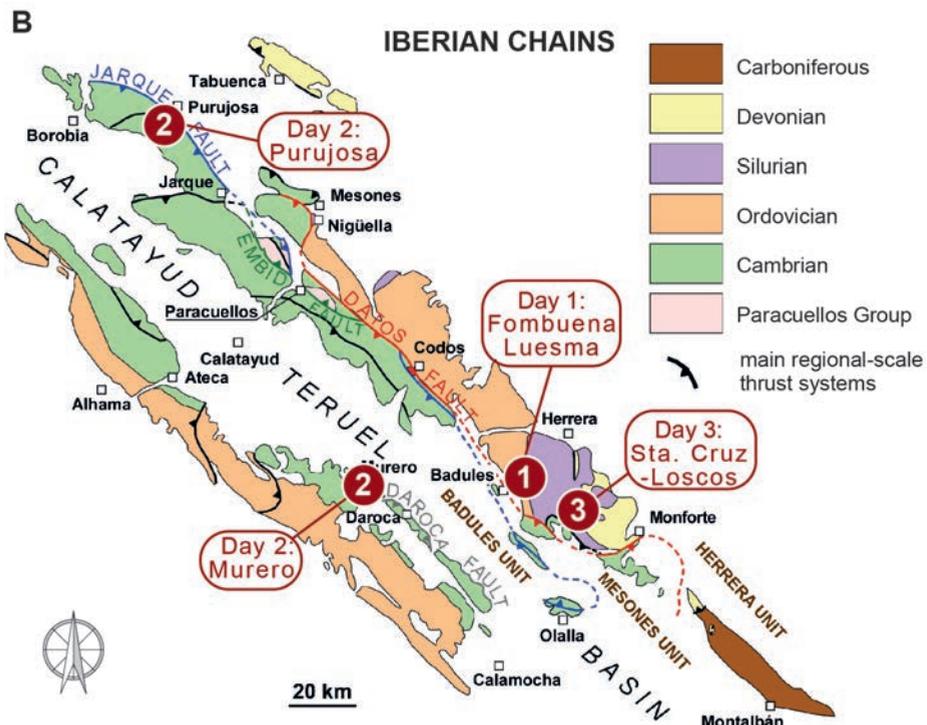


Figure 1. Itinerary followed by the field trip. A. Map of Spain showing Pre-Hercynian outcrops and tectonostratigraphic zones. Zones: CZ, Cantabrian; CIZ, Central Iberian; WALZ, West Asturian-Leonese; OMZ, Ossa-Morena Zones; SPZ, South Portuguese; BC, Betic Cordillera; IC, Iberian Chains; PY, Pyrenees. B. Geological map of the Iberian Chains with indication of Palaeozoic outcrops and tectonostratigraphic units, after Álvaro *et al.* (2018).



DAY 1: December 15th 2019

ORDOVICIAN TO SILURIAN BENTHIC COMMUNITIES FROM THE EASTERN IBERIAN CHAIN

Jorge Colmenar, Enrique Villas, Juan Carlos Gutiérrez-Marco, J. Javier Álvaro, Sofia Pereira and Samuel Zamora

INTRODUCTION

A complete Ordovician-to-Silurian succession crops out in the vicinity of Fombuena, Luesma and Herrera de los Navarros villages (Fig. 2), in the Eastern Iberian Chain. The Ordovician is nearly 4000 m thick and composed primarily of siliciclastic rocks, with the only exception of 40 m of upper Katian limestones, and up to 8 m of upper Sandbian bryozoan marlstones (Fig. 3). The thicknesses of the different Ordovician stages change significantly, with the Tremadocian to Dapingian being more than 3000 m thick, and the Darrivillan to Hirnantian less than 500 m thick. Lotze (1929) described the stratigraphy, which was refined by Carls (1975), Wolf (1980), Villas (1983) and Hammann (1992). Modern stratigraphic reviews have also been made by Sarmiento (2002) and Gutiérrez-Marco *et al.* (2002, 2005). Liñán *et al.* (1996) made a thorough palaeontological synthesis of the Ordovician of the Iberian Cordillera.

The thick Lower and lower Middle Ordovician succession has been divided into four formations, two of them dominantly shaly, the Borrachón and Santed formations, and the other two mainly quartzitic, the Dere and Armorican Quartzite formations. Although the quartzitic formations display a rich ichnofossil record, shelly fossil occurrences are sparse in the four units. As a result, the position of the Cambrian-Ordovician boundary remains controversial. It was considered to lie within the thickly bedded quartzites with shaly intercalations of the Valconchán Formation, just below the Borrachón Formation (Havlíček and Josopait, 1972; Wolf, 1980). More recently the Cambrian-Ordovician boundary has been changed to the middle-upper part of the Borrachón Formation, based on the occurrence in its basal part of trilobite assemblages close to late Furongian ones from Mexico and the Central Andean Cordillera (Shergold and Szalay, 1991; Gutiérrez-Marco *et al.*, 2002). The Armorican Quartzite is the local representative of the typical Armorican sandy facies that characterizes the Floian and earliest Dapingian in a great part of Iberia and Armorica. Its original name, first used by Dereims (1898), was maintained by Wolf (1980) when defined formally the formation. Near Usued (Zaragoza), in the western Iberian Chain, from the intermediate strata of the Armorican Quartzite, Villas *et al.* (2001) described a rich association of asaphid trilobites, xyphosurids and large lingulids, including *Tomasina criei* and *Lingulepis crassipyxis*. The assemblage also includes some conulariids and molluscs, such as the bivalve *Modiolopsis aragonensis* described by Babin and Hammann (2001).

An oolitic ironstone, overlying the Armorican Quartzite, marks the base of the sandy and shaly Castillejo Formation (Fig. 3), the local representative of the "Neseuretus shales and sandstones", widespread throughout Iberia (Hammann *et al.*, 1982). The Castillejo Formation can be correlated with most of the Darrivillan, although it probably overlies a stratigraphic gap corresponding to the lower Oretanian regional stage (equivalent to the British lower Aberiddian), since the lowest graptolites found in the formation belongs to the *D. murchisoni* Zone (Gutiérrez-Marco, 1986). Trilobites (Hammann, 1983) and brachiopods (Villas, 1985) are relatively abundant in its upper part, early Dobrotivian (latest Darrivillan) in age.

The Upper Ordovician is represented in the region by the upper Sandbian to middle Katian (Sa2–Ka2; “Caradoc-Ashgill”) alternating siltstones and sandstones of the Fombuena Formation (Fig. 3) overlain by the upper Katian (Ka3–Ka4) Cystoid Limestone Formation, the Hirnantian diamictites of the Orea Formation and the quartzites of the Los Puertos Formation, the latter mainly of Hirnantian age. These units are well exposed in the localities we will visit in this first excursion day, and their most outstanding features are introduced below.

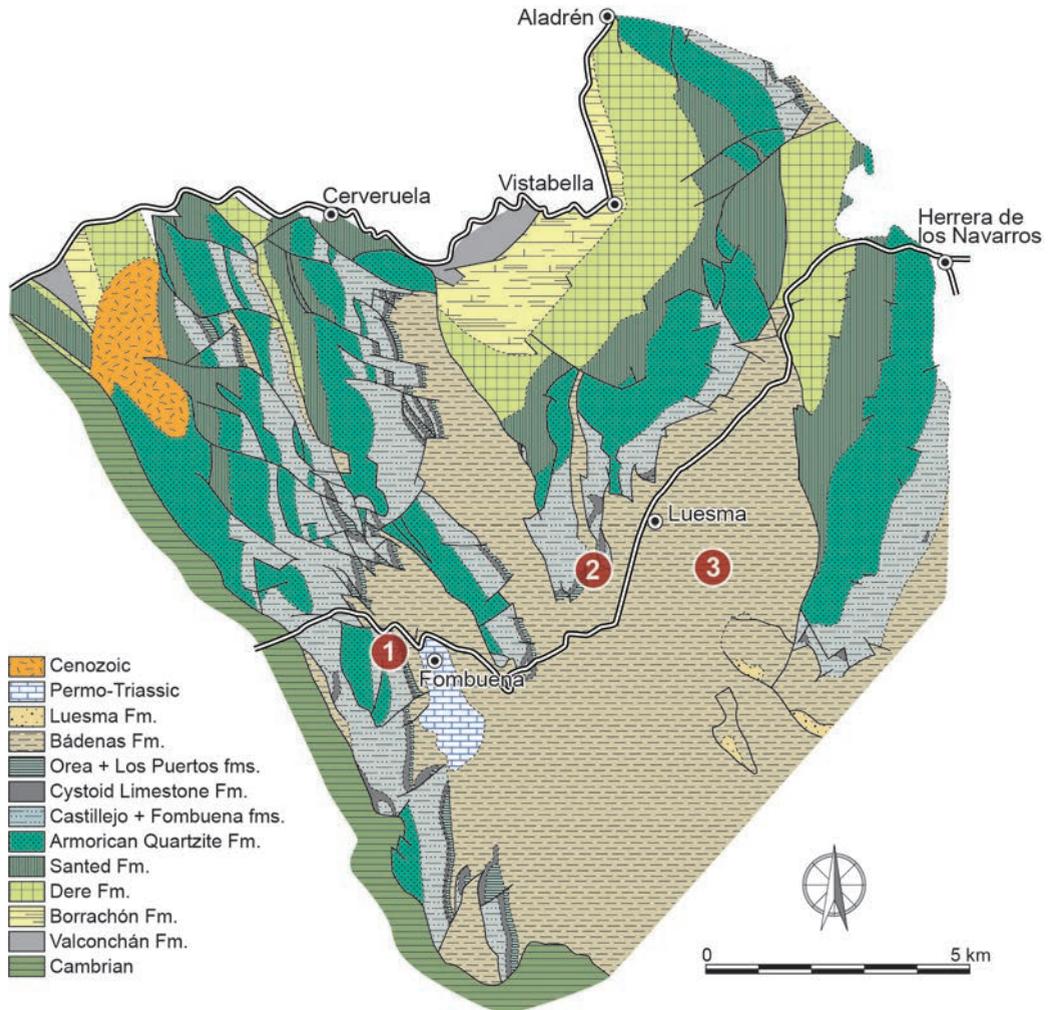


Figure 2. Geological map of the surroundings of Fombuena to Luesma, with location of stops. Modified from Hammann (1992).

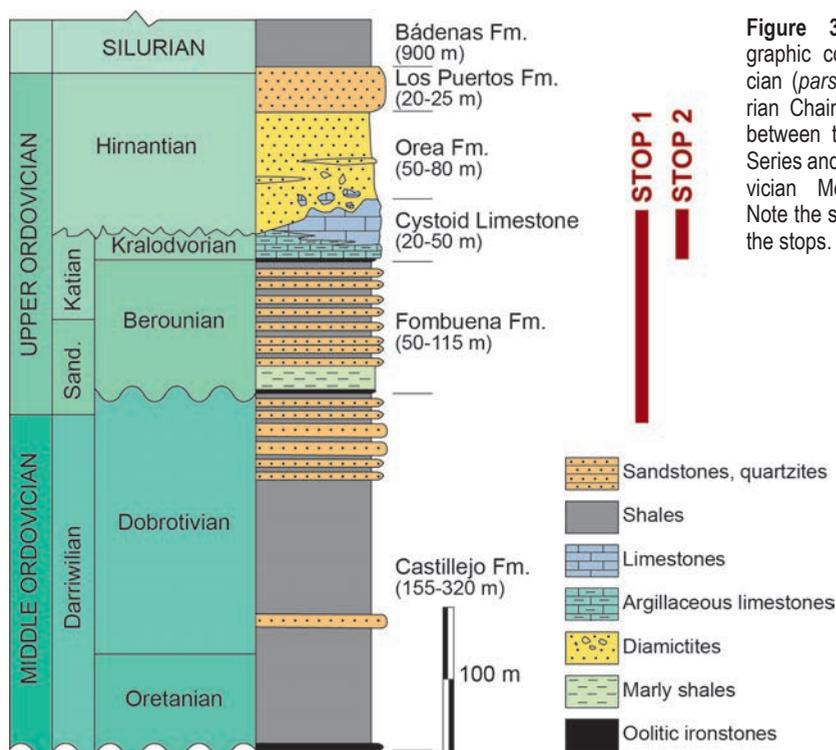


Figure 3. Schematic stratigraphic column of the Ordovician (*pars.*) of the Eastern Iberian Chain, with the correlation between the Ordovician Global Series and Stages and the Ordovician Mediterranean Stages. Note the stratigraphic position of the stops.

The Ordovician-Silurian boundary in the Iberian Chains lies in the uppermost quartzites of the Los Puertos Formation (20–40 m), where recent sampling has resulted in the discovery of some brachiopods typical of the *Hirnantia* Fauna (Bernárdez *et al.*, 2015). The oldest Silurian fossils are graptolites occurring in the shaly intercalations of the upper part of the Los Puertos Fm. (Gutiérrez-Marco and Štorch, 1998). These graptolite assemblages indicate a Rhuddanian and Aeronian age (*Parakidograptus acuminatus*, *Coronograptus cyphus*, *Demirastrites triangulatus* and *Lituigraptus convolutus* zones) (Robardet and Gutiérrez-Marco, 2002). The rest of the Silurian deposits in the Iberian Chains are represented by the Bádernas Formation that conformably overlies the Los Puertos Formation. The thickness of this formation varies from about 300–400 m in the western Iberian Chain to about 900–1400 m in the eastern Iberian Chain.

The field excursion allows us to recognize several invertebrate benthic communities from the Middle, Upper Ordovician and Silurian outcrops (Fig. 2). The diversity changes of the Ordovician invertebrate reaches several peaks at the Castillejo, Fombuena, and Cystoid Limestone formations allowing us to analyze the replacement of benthic communities related to the type of substrate and the Boda Event (Fig. 2, stop 1). Correlatable beds from the La Rebosilla Member (Fig. 2, stop 2) show a distinct type of preservation of shelly fossils embedded in the more proximal facies of the Cystoid Limestone Formation. This will be completed with a visit to the Silurian Bádernas Formation, with benthic associations dominated by crinoids and chonetid brachiopods (Fig. 2, stop 3). All these units record the shift of the Mediterranean margin of Gondwana from latitudes close to the south Pole during the Late Ordovician to more temperate latitudes during the Silurian, as well as the progressive diversification and successive replacements of the benthic assemblages along that 50 m.y. interval.

STOP 1: Mid to Late Ordovician benthic communities from La Peña del Tormo section

Location

The section crops out along the A-1506 road close to its passage through the Peña del Tormo stream (Figs. 4, 5).

Coordinates: 41° 8' 53" N, 1° 12' 16" W, Geological map of Spain, 1:50000, sheet of Daroca (465).

Geological setting: Herrera Unit (Eastern Iberian Chain).

Lithostratigraphic units: Castillejo, Fombuena and Cystoid Limestone formations (Figs. 3, 5, 6).

Age: Darrivilian–latest Katian (Mid–Late Ordovician).

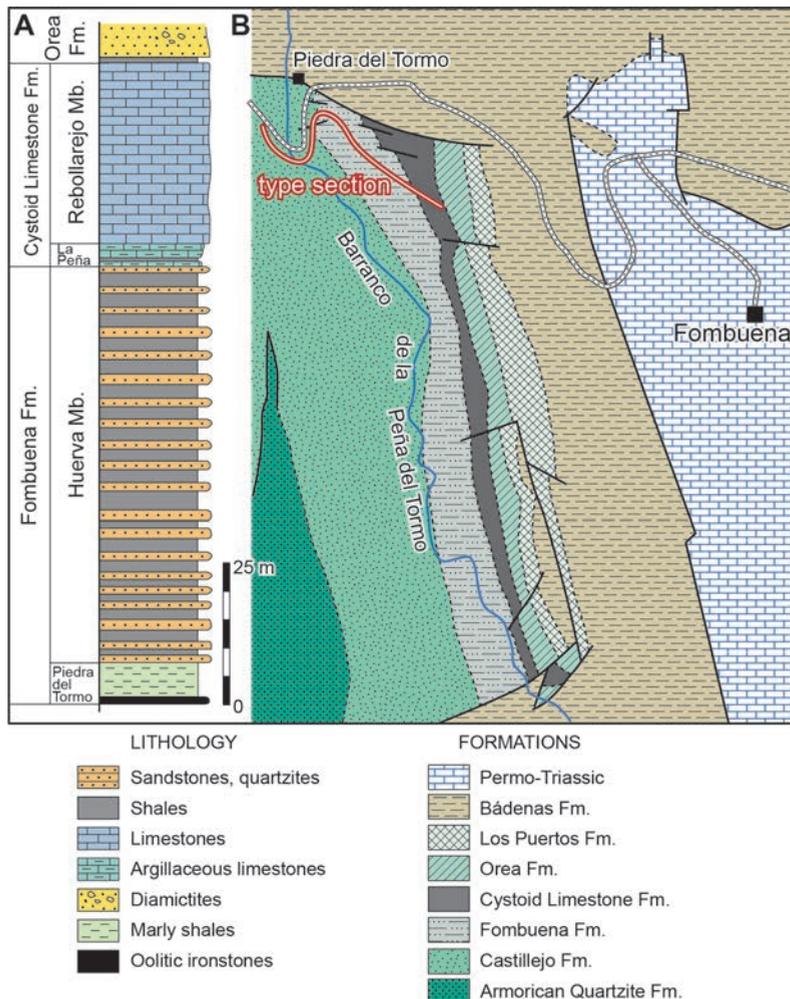


Figure 4. Geological map and lithological column of the Peña del Tormo locality. Modified from Hammann (1992). Itinerary marked with a red line.

Aims

Show general aspects of the Middle and Upper Ordovician succession in the Iberian Chains. Discuss the replacement of benthic communities related to changes of substrate and climate triggered by the global warming Boda event.

Description

In this section there is an almost continuous exposure from the top of the Castillejo Formation, latest Darrivilian in age, to the base of the Bádenas Formation, early Silurian. The outstanding Peña del Tormo (Thor Rock), a faulted white quartzite block of the Los Puertos Formation, gives name to the stream where the section begins. The locality lies about 1 km west of the small village of Fombuena (“good fountain” in old Spanish), built on Permo-Triassic rocks. The section starts in the eastern bank of the road Badules-Fombuena where the Castillejo/Fombuena formations contact is well exposed (Fig. 5).

Castillejo Formation

The Castillejo Formation paraconformably overlies the Armorican Quartzite and contains three members:

- Marité Member

The lower member displays a variable thickness, from one metre in its type section up to 40 m in the Marité Quarry northwest of Luesma (Carls, 1975). It is composed of ferruginous shales that locally comprise up to three oolitic ironstone beds. Several authors (Kolb, 1978; Wolf, 1980; Gutiérrez-Marco, 1986) indicate the presence of graptolites belonging to the *Didymograptus murchisoni* Zone (Figs. 7B–D) typical of late Oretanian age (late mid to early late Darrivilian in the global scale).

- Alpartir Member

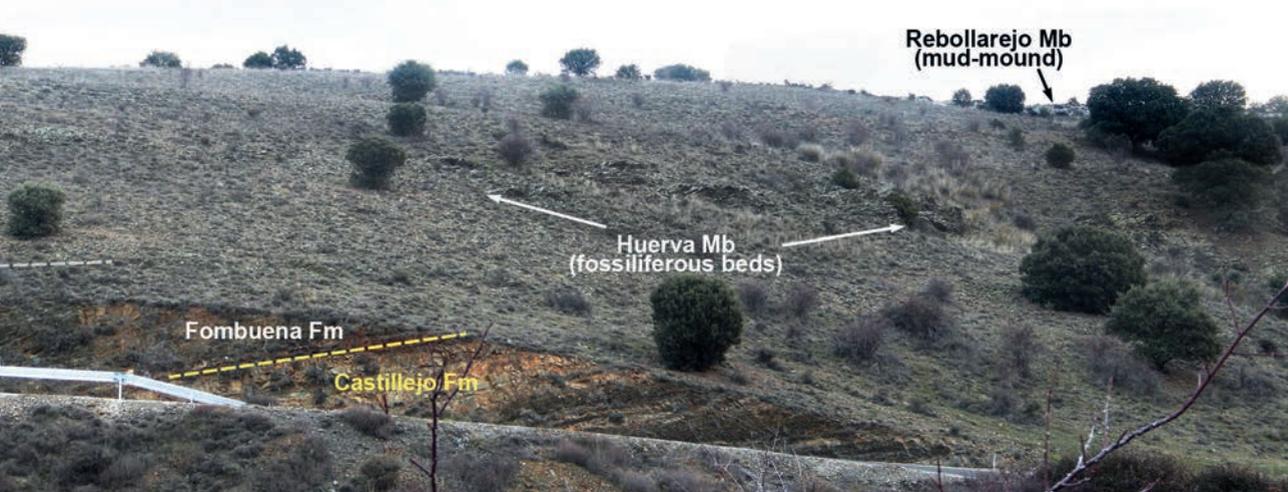
The middle member (110–200 m thick) is composed mainly of shales with some intercalations of sandstones and siliceous and ferruginous nodules. Last graptolites of the *D. murchisoni* Zone have been found 25–30 m above the base of the member (Gutiérrez-Marco, 1986). In laterally equivalent levels, Kolb (1978) reported the trilobites *Neseuretus tristani* and *Placoparia “cambriensis” (P. tournemini)*, besides the bivalve *Redonia* sp. In the upper part of the member, the graptolites *Gymnograptus linnarssoni* (Fig. 7A) and *Hustedograptus teretiusculus* have been found (Hamman *et al.*, 1982; Gutiérrez-Marco, 1986) as well





Figure 6. A. Mud mound of the Cystoid Limestone Formation. B. Contact between Castillejo and Fombuena formations; the hammer is marking the oolitic ironstone bed at the base of the Fombuena Formation. C. Fossiliferous levels in the Huerva Member of the Fombuena Formation.

Figure 5. Panoramic view of La Peña del Tormo Section.



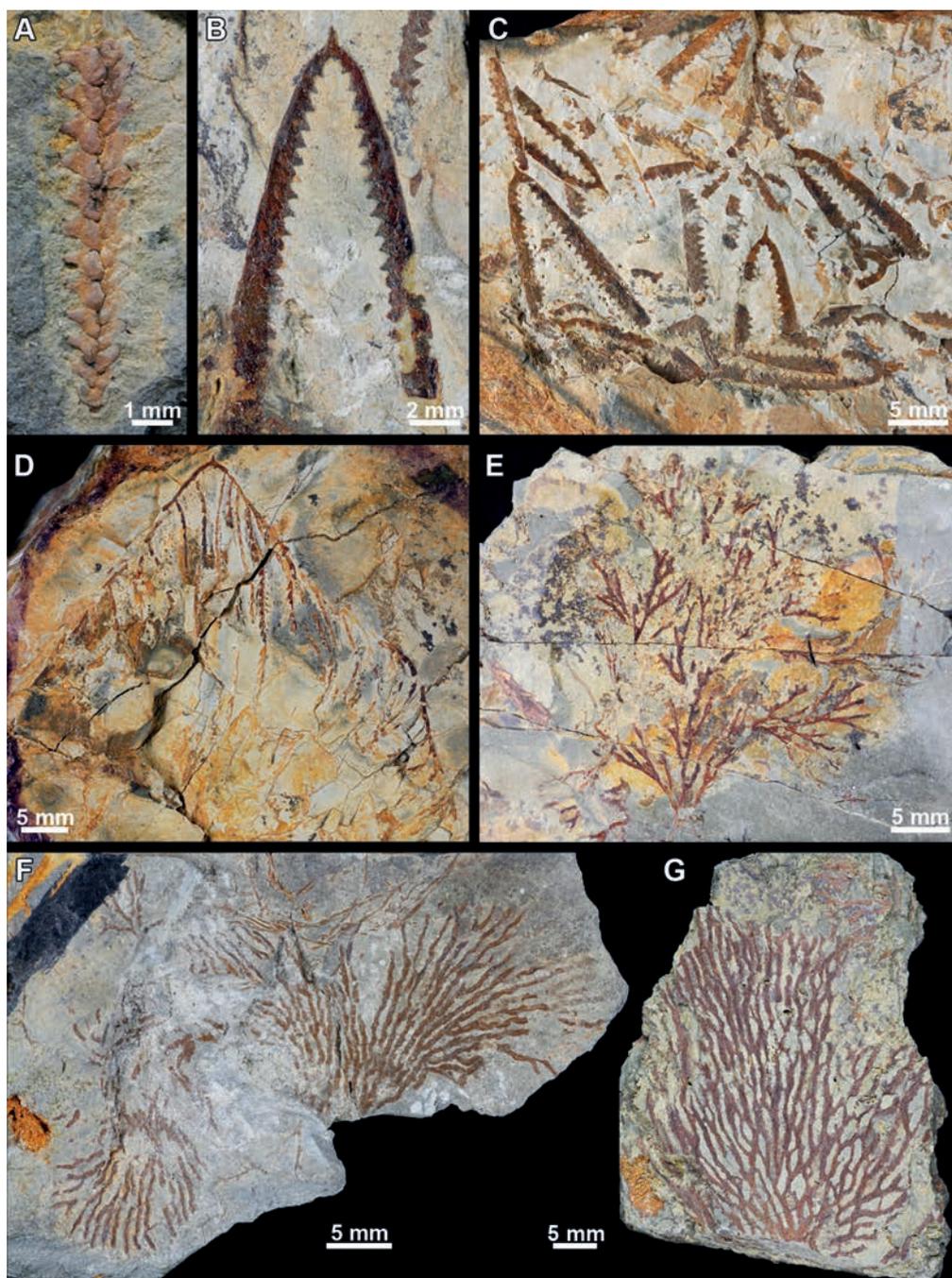


Figure 7. Some graptolites from the Castillejo (A-D) and Fombuena (E-G) formations. A. *Gymnograptus linnarssoni*, Alpartir Mb. B-C. *Didymograptus munchisoni*, Marité Mb. D. *Pterograptus* n. sp., Marité Mb. E. *Dendrograptus* sp., Piedra del Tormo Mb. F. *Aspidograptus* n. sp., Piedra del Tormo Mb. G. *Reticulograptus* n. sp., Piedra del Tormo Mb.

as the trilobites *Isabelinia glabrata* (Fig. 8A), *Eccoptochile almadenensis* (Fig. 8B), *Placoparia tournemini*, *Neseuretus tristani*, *Eodalmanitina macrophtalma*, *Colpocoryphe rouaulti* and *Salterocoryphe salteri*, the molluscs *Sinuities hispanica* and *Redonia deshayesi* (Hammann *et al.*, 1982), and the brachiopods *Howellites hammanni* (Figs. 8E–F), *Heterorthis morgatensis* (Fig. 8H), *Aegiromena mariana* (Fig. 8D) and *Crozonorthis muscolosa* (Fig. 8G); an assemblage of early Dobrotivian (late Dariwilian) age.

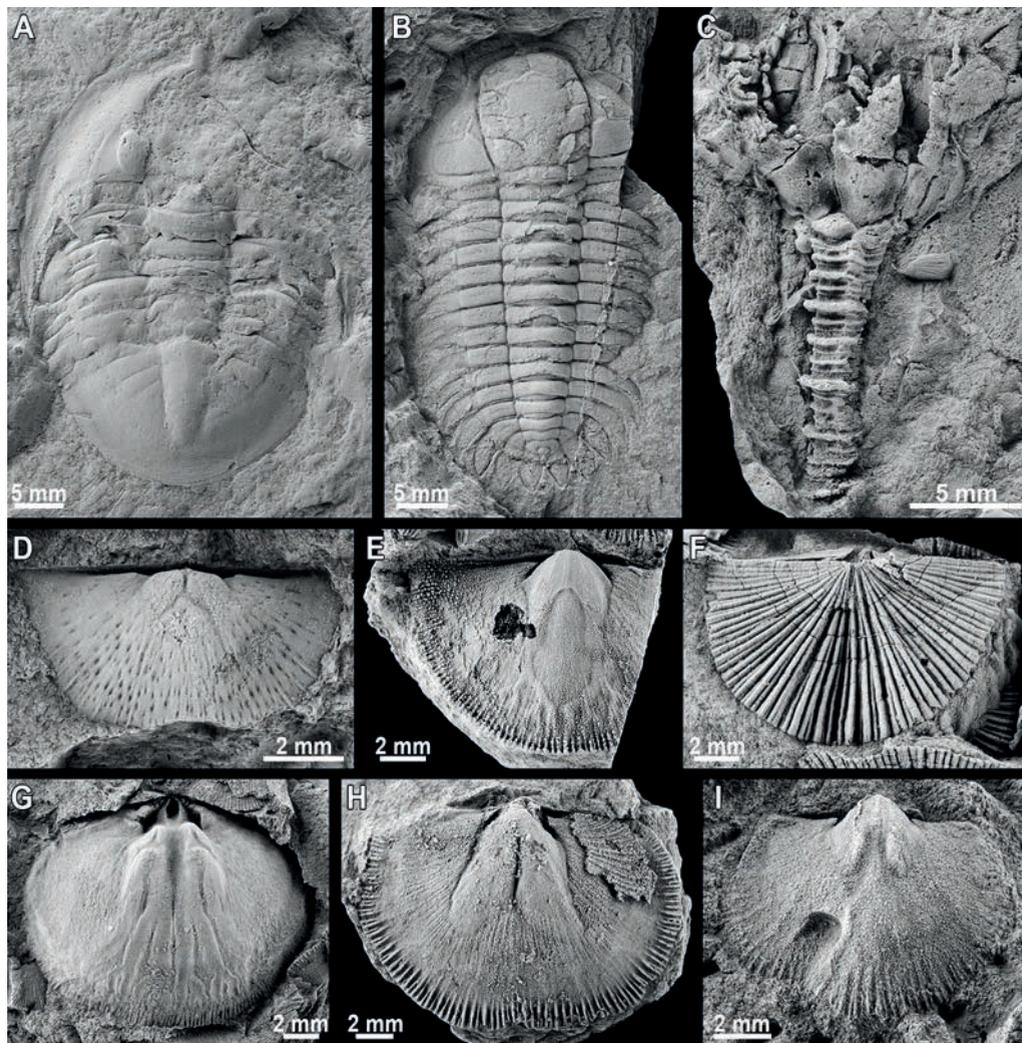


Figure 8. Abundant fossils of the Castillejo Formation. A. *Isabelinia glabrata*, asaphid trilobite from the Alpartir Mb. B. *Eccoptochile almadenensis*, cheirurid trilobite from the Alpartir Mb. C. Crinoid *Heviacrinus melendezi*, latex cast of external mould. D. *Aegiromena mariana*, internal mould of ventral valve, Castillejo Fm., Sierra Mb. E-F. *Howellites hammanni*, Castillejo Fm., Alpartir Mb. internal mould of ventral valve (E) and latex cast of exterior of dorsal valve (F). G. *Crozonorthis muscolosa*, internal mould of dorsal valve, Fombuena Fm., Sierra Mb. H. *Heterorthis morgatensis*, internal mould of ventral valve, Castillejo Fm., Alpartir Mb. I. *Heterorthis kerfornei*, internal mould of ventral valve, Castillejo Fm., Sierra Mb.

- Sierra Member

The upper member displays a variable thickness decreasing towards the northwest from 150 to 10 m (Villas, 1983). It is characterized by alternating shales and sandstones, commonly punctuated by highly fossiliferous sandstone lenses with calcareous cement. Near Luesma, the top of these quartzites is marked by a massive occurrence of *Rusophycus petraeus* that was elsewhere only known in Africa and the Middle East. Hammann *et al.* (1982) cited the trilobites *Neseuretus henkei*, *Crozonaspis incerta*, *Crozonaspis armata*, *Phacopidina micheli* and *Eohomalonotus szzuyi* as well as gastropods, bivalves and rostroconchs. Sarmiento *et al.* (1995) also reported some conodonts (*Distomodus? tamarae*, *Icriodella aff. praecox*, *Drepanoistodus* and *Amorphognathus?*), occurring in a single coquinoid bed probably of late Dobrotivian age (latest Darrivilian to earliest Sandbian). The lowermost beds of this member have yielded the crinoid *Heviacrinus melendezi* (Fig. 8C) (Cole *et al.*, 2017).

The brachiopod content is still of very low diversity, very similar to that of the underlying member, except for the replacement of *Heterorthina morgatensis* by *H. kerfornei* (Fig. 8I). These two species are among the earliest representatives of the family Heterorthidae in Ibero-Armorica, which later, during the Sandbian, greatly diversified, becoming one of the most characteristic brachiopods of the Mediterranean Province.

Fombuena Formation

The Fombuena Formation is subdivided into two members (Fig. 4):

- Piedra del Tormo Member

The lower member overlies the alternating sandstones and siltstones of the Castillejo Formation (Fig. 6B). Its base is marked by an ooidal ironstone, about 1m thick, which can be easily correlatable throughout SW Europe and North Africa. The ironstone is overlain by 8 m of marly shales and marlstones, rich in bryozoans and some brachiopods, gastropods, benthic graptolites and echinoderms. The ironstone is always present at the base of the formation throughout the eastern Iberian Chain, but the bryozoan marlstones are restricted to the vicinity of Fombuena. In the northeastern margin of the chain, the basal ironstone is overlain by the alternating sandstones and shales that characterize the rest of the formation.

Some of the brachiopods recorded in the ironstone and the overlying marlstones, such as *Aegiromena aquila intermedia*, *Rafinesquina (Mesogeina) pseudoloricata*, *Gelidorthis meloui*, *Jezercia chrusteniensis*, *Reuschella herreraensis*, *Rostricellula ambigena* and *Svobodaina armoricana*, allow correlation of the base of the formation with distant units in Iberia, such as the ferruginous horizon at the lower part of the “Cantera Shales” (Corral de Calatrava, Central Spain) or the Favaçal Bed at the base of the Louredo Formation (Buçaco, Portugal). They also allow a correlation with the chloritic ooidal ironstone occurring about 100 m above the base of the Vieille-Cour Formation in Normandy, and with the Zdice-Nucice iron ore horizon at the base of the Vinice Formation (middle Berounian) in Bohemia (see Villas, 1992). Some elements from this brachiopod assemblage have also been recently identified in the upper part of the Lower Ktaoua Formation in the Moroccan Anti-Atlas, and a correlation with the former unit has been suggested (Villas *et al.*, 2006). All of them can be also correlated with the Longvillian (upper Burrellian stage of the British Caradoc) based on the chitinozoans found in the Portuguese and Armorican units (Paris, 1979; 1981). In terms of the global scale, a late Sandbian to earliest Katian (Sa2–Ka1) age is assigned to the middle part of the Berounian regional stage.

The brachiopod association is related to bryozoan-pelmatozoan meadows, interpreted to have developed in an offshore environment (Vennin *et al.*, 1998). The occurrence in the association of the heteror-

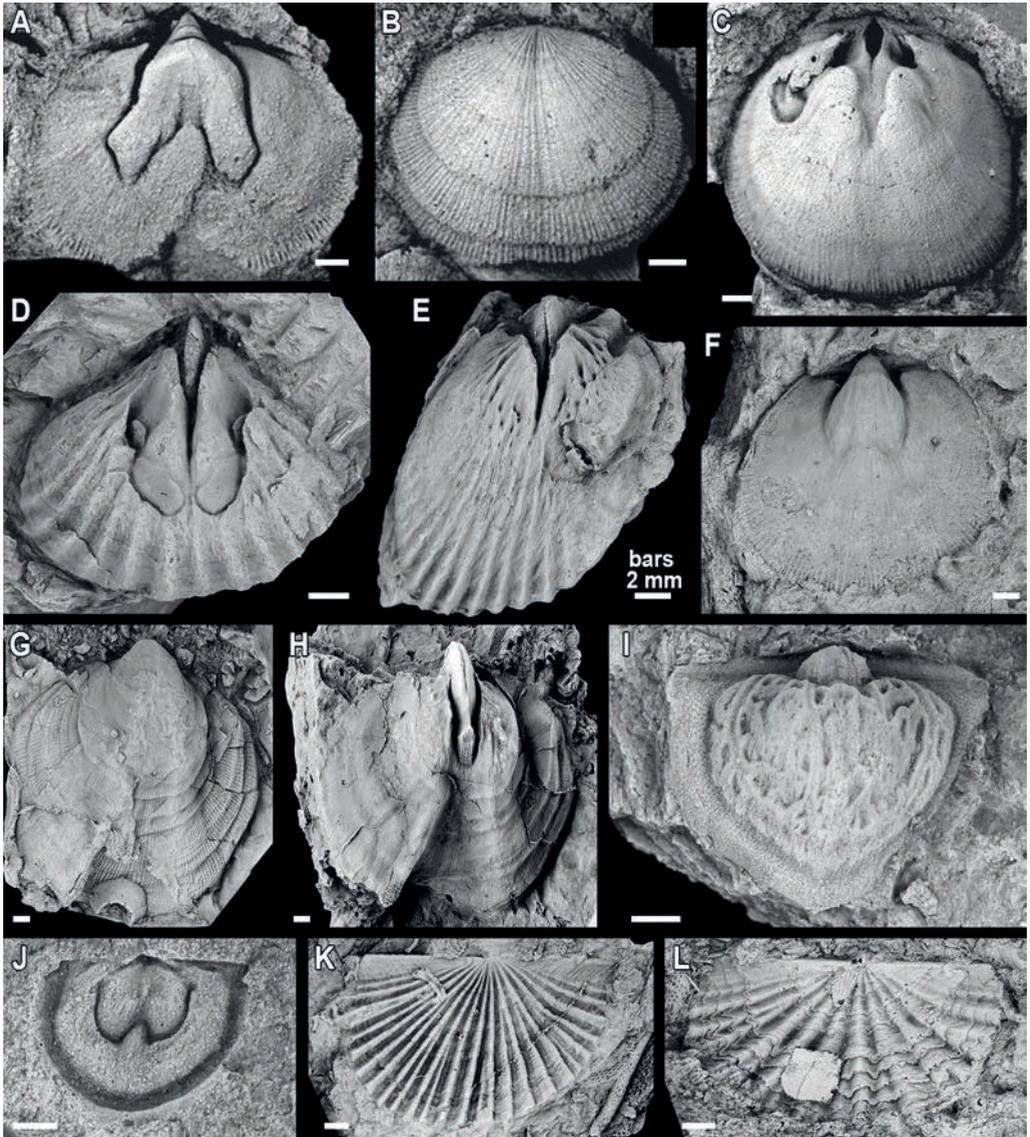


Figure 9. Abundant brachiopods from the Fombuena and Cystoid Limestone formations, Sandbian to late Katian (Ordovician).

A-C. *Svobodaina havliceki*, Fombuena Fm., top of the Huerva Mb, internal mould of ventral valve (A), latex cast of exterior of dorsal valve (B) and internal mould of dorsal valve (C). D-E. *Eoanastrophia pentamera*, Cystoid Limestone Fm., dorsal internal mould (1) and ventral internal mould (2). F. *Svobodaina armoricana*, Fombuena Fm., Piedra del Tormo Mb., internal mould of ventral valve. G-H. *Porambonites (Porambonites) magnus*, Cystoid Limestone Fm., latex cast of exterior (G) and internal mould (H) of ventral valve. I. *J. Leangella (Leangella) anaclyta*, Cystoid Limestone Fm., ventral internal mould (I) and dorsal internal mould. K-L. *Nicolella actoniae*, Cystoid Limestone Fm., latex casts of dorsal exteriors.

thid brachiopod *Svobodaina armoricana* reinforces the interpretation of a low-energy quiet environment, according to its very short diductor scars and the smallest ventral muscle field for the genus (Colmenar *et al.*, 2014). This interpretation follows the idea by Carls *et al.* (1993) relating large diductor muscles to high-energy and turbulent environments, where they would help preventing sudden shell closure that could damage the mantle margins.

Echinoderms are also abundant in this lower member. The first echinoderms recovered from this member were the rhombiferans *Heliocrinites? sampelayanus* and *Heliocrinites? isabellae*, which were described from poorly preserved specimens (Meléndez, 1944b). Later, extensive sampling of the same beds produced a moderately diverse echinoderm fauna that includes the coronoid *Mespilocystites lemenni*, the diploporans *Calix? cf. gutierrezzi* and Sphaerontida fam. indet., and the rhombiferans *Caryocrinites cf. rugatus*, Hemicosmitida fam. indet., *Heliocrinites* sp., and *Rhombifera bohémica* (Gutiérrez-Marco *et al.*, 1996).

Benthic graptolite assemblages are mainly composed of still undescribed new species of dendroids, such *Acanthograptus* n. sp., *Dictyonema* n. sp., *Dendrograptus* sp. (Fig. 7E) and *Aspidograptus* n. sp. (Fig. 7F), as well as the tuboid *Reticulograptus* n. sp. (Fig. 7G), see Gutiérrez-Marco (1986)

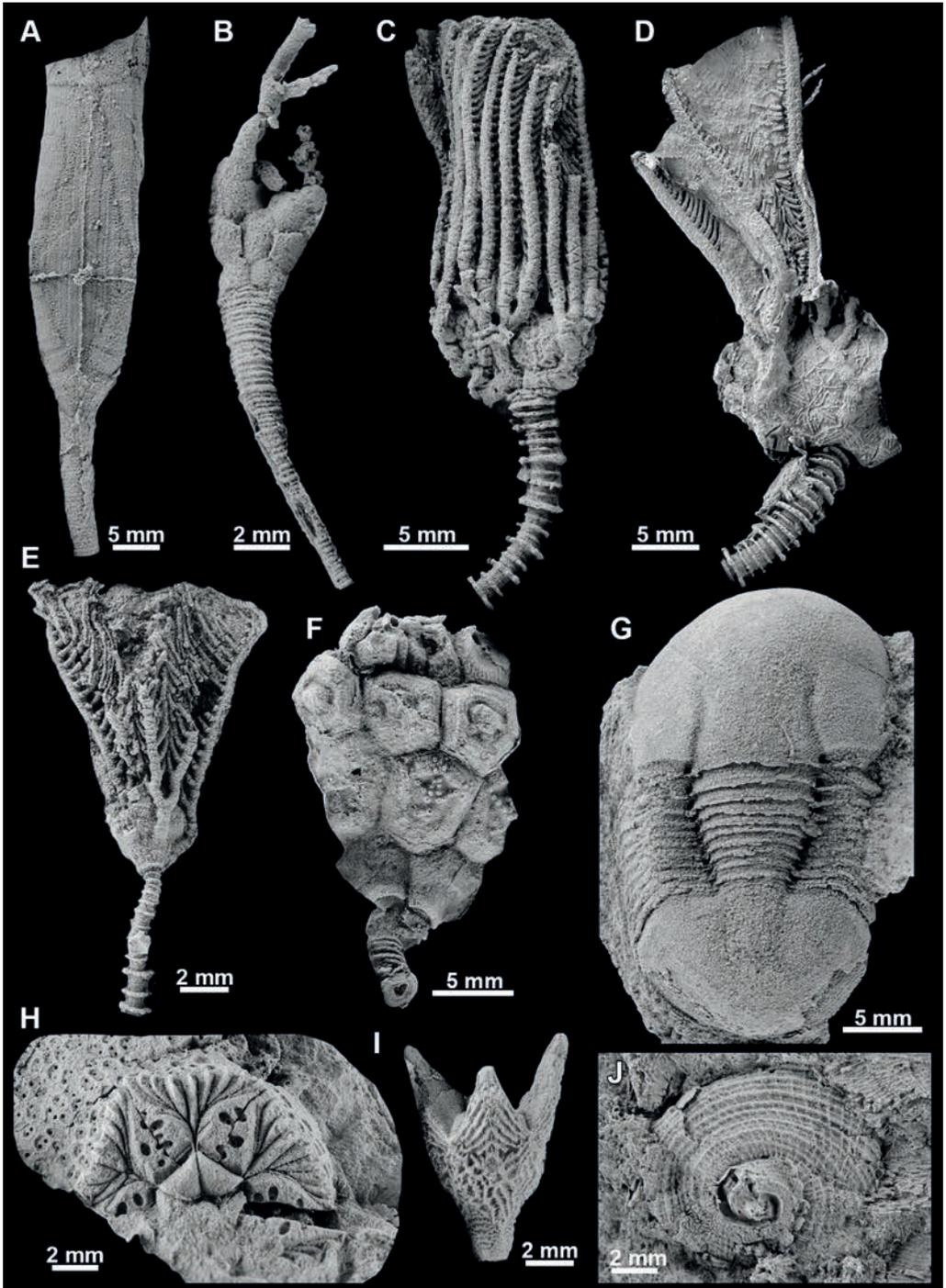
Besides the bryozoans, echinoderms and graptolites, other fossil groups uncommon in the Piedra del Tormo Member are large gastropods (*Radvanospira antiquata*) and rare trilobites, such as *Vysocania iberica* and *Prionocheilus verneulli*.

- Huerva Member:

This upper member is also restricted to the Fombuena area and is mostly composed of sandstones with interbedded sandy shales. A fossiliferous layer in its middle part (Figs. 4, 5, 6C), approximately 20 m above the base of the unit, has yielded a typical middle Berounian (upper Sandbian–lower Katian) brachiopod-dominant assemblage, yielding *Svobodaina armoricana* (Fig. 9F), *Rafinesquina (Mesogeina) pomoides*, accompanied by *Gelidorthis carlsi*, *Dalmanella unguis unguis*, *Drabovia* sp., *Drabovinella* sp., *Triplesia iberica* and *Rostricellula ambigena*.

Brachiopods and bryozoans dominate this assemblage, but echinoderms are also very abundant. The first echinoderms from this level were described by Gutiérrez-Marco *et al.* (1996), who reported *Rhombifera* sp., Diploporita indet. and *Mespilocystites lemenni*. Recent samplings in the La Peña del Tormo section and surrounding localities of Fombuena have yielded a remarkably well-preserved and diverse echinoderm fauna (Zamora *et al.*, 2014). The blastozoan fauna is mainly dominated by the diploporan *Codiacystis? nov.* sp. (Fig. 10H) and the coronoid *Mespilocystites* (Fig. 10I). Rhombiferans are also very conspicuous in the formation, including nearly complete specimens of *Rhombifera bohémica* (Fig. 10A) and *Caryocrinites* sp. (Fig. 10F), both preserving the stem. New unreported taxa include a fragment of an indeterminate asterozoan and the solutan carpoid *Dendrocystites* sp. Cole *et al.* (2017) described the crinoid fauna including the new diplobathrid camerates *Fombuenacrinus nodulus* (Fig. 10D), *Goyacrinus gutierrezzi* (Fig. 10C), *Dalocrinus hammanni* and *Ambonacrinus decorus*; the new monobathrid camerate *Eopatelliocrinus hispaniensis* (Fig. 10E) and the new cladid *Picassocrinus villasi* (Fig. 10B). This high-latitude crinoid assemblage has the

Figure 10. Frequent echinoderms, trilobites and gastropods from the Fombuena Formation. A. *Rhombifera bohémica* Barrande. B. *Picassocrinus villasi*, holotype. C. *Goyacrinus gutierrezzi*, lateral view of crown and proximal stem of the holotype. D. *Fombuenacrinus nodulus*, lateral view of crown, holotype. E. *Eopatelliocrinus hispaniensis*, lateral view of crown and partial stem, holotype. F. Blastozoan *Caryocrinites* sp. preserving part of the proximal stem. G. *Vysocania iberica*, internal mould. H. Oral area of the diploporan *Codiacystis? n. sp.* I. Coronoid *Mespilocystites lemenni*. J. Gastropod (*Nonorios? sp.*). All specimen are photographs of latex casts with exception of G wich is an internal mold.



highest crinoid diversity of any currently known Katian Gondwanan fauna. Trilobites from this level are very scarce and mainly represented by *Vysocania iberica* (Fig. 10G). Some gastropod remains were identified as *Nonorios?* sp. (Fig. 10J)

The upper half of Huerva Member should represent the Katian 2 substage (Caradoc-Ashgill boundary), due to the occurrence of a low diversity brachiopod assemblage, including *Rafinesquina (Mesogeina) pomoides* and *Svobodaina havliceki* (Figs. 9A–C), known in the Bancos Mixtos from Central Spain and the base of Porto do Santa Anna Formation in Portugal (Villas, 1995). *Rafinesquina (Mesogeina)* has been erected by Colmenar (2016) to group a number of Mediterranean *Rafinesquina* species with peculiar internal features, quite different to those of the rest of the genus worldwide. *Rafinesquina (M.) pomoides* is interpreted as libero-sessile and recumbent during the adult stages, living in a deeper environment than *S. havliceki*, which according to its very large and flabellate ventral diductor scars (Fig. 9A) would be adapted to shallower, high-energy conditions (Colmenar *et al.*, 2013).

Cystoid Limestone Formation

The Cystoid Limestone Formation is the local representative of the carbonate sedimentation that took place during late Katian times (Ka3–4: early-mid Ashgill) on the high-latitude shelf bordering the southern (palaeogeographically) Gondwana margin, as a consequence of the global warming Boda event (Fortey and Cocks, 2005). It displays strong lateral facies changes, with massive limestones in the western part of its outcrop area.

The Cystoid Limestone has been divided in this western area into two units: the La Peña Member (Fig. 4), made up by 2 m of marly limestones, with abundant pelmatozoans, bryozoans and brachiopods; and the overlying Rebollarejo Member, up to 40 m thick, characterized by the occurrence of mud-mound complexes (Veninn *et al.*, 1998). The complexes are up to 10 m high and 300 m wide, and comprise individual lenticular mounds (Fig. 6A). Mounds are up to 2 m thick and 6 m wide, and form flattened carbonate lenses embedded in bioclastic facies (Fig. 11). The main carbonates within the mound cores

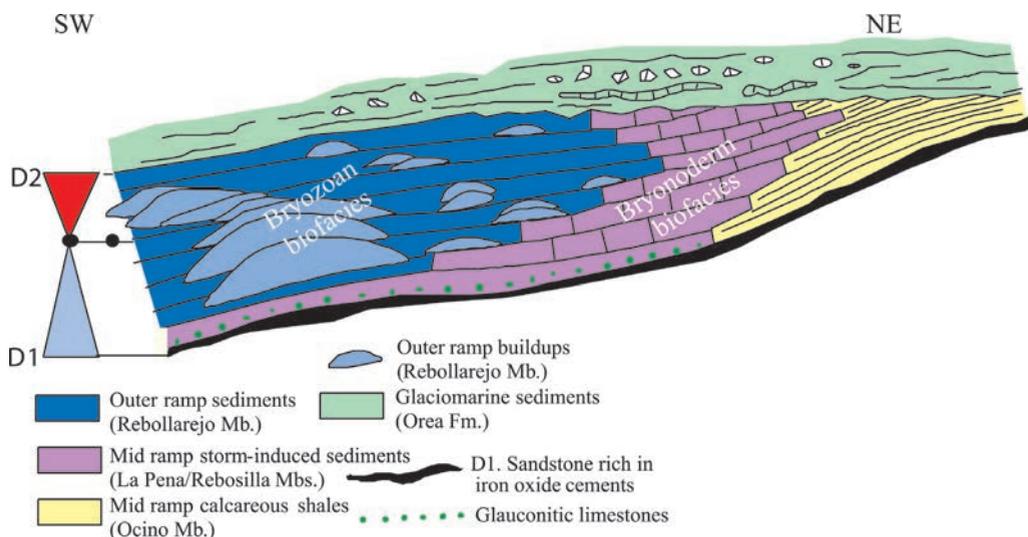


Figure 11. Sequence stratigraphic components of the Late Ordovician Iberian basin, location and geometry of outer ramp mud-mounds. D1, D2, discontinuities (after Veninn *et al.*, 1998).

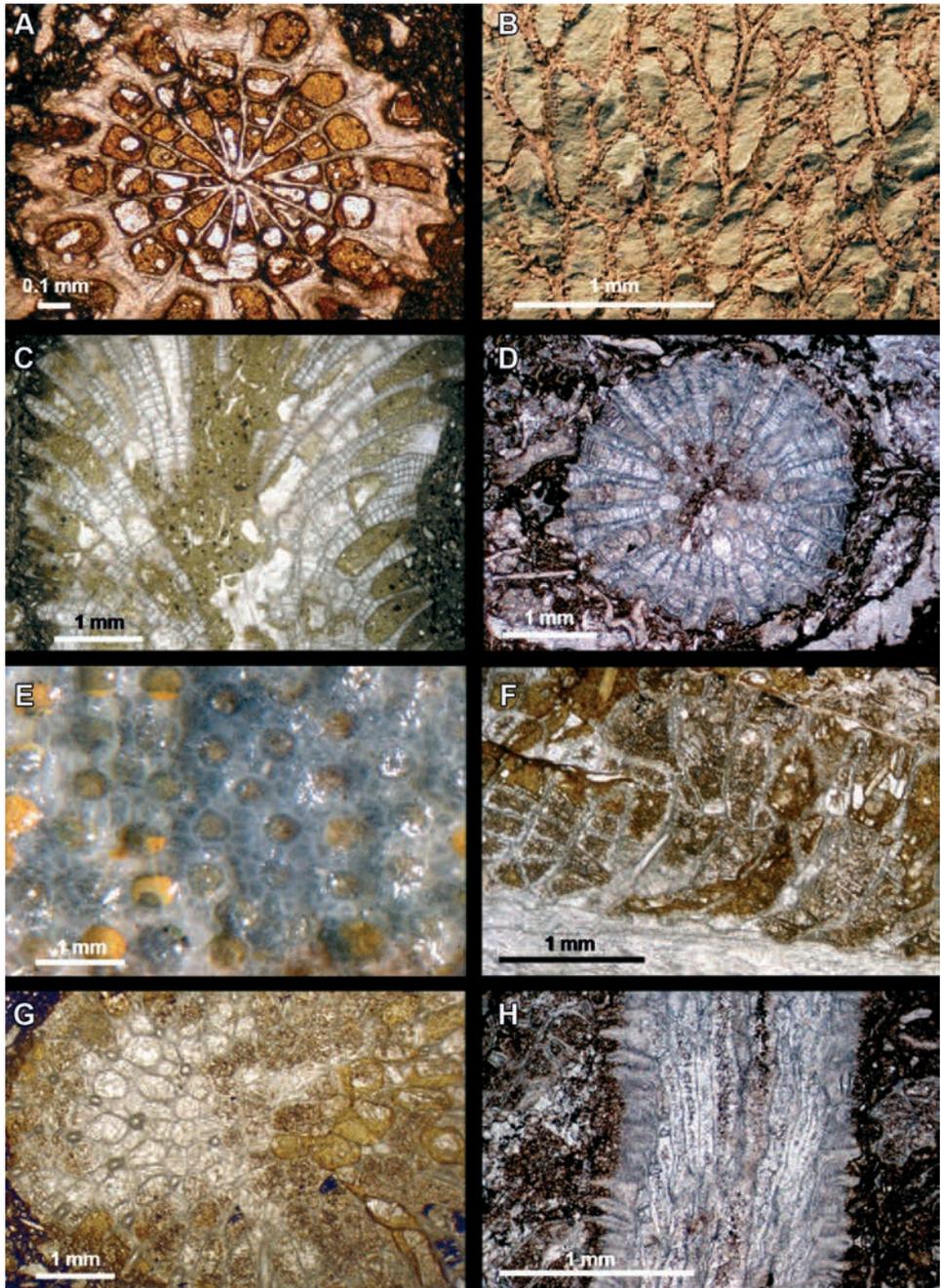


Figure 12. Representative bryozoans from the Cystoid Limestone Formation of the Eastern Iberian Chain. A. *Moyerella?* sp., Fombuena. B. *Chasmatopora hypnoides*, Luesma. C. *Hallopora elegantula*, Fombuena. D. *Parvohallopora* cf. *ramosa*, Fombuena. E. *Prasopora spjeldnaesi*, Fombuena. F. Monticuliporidae sp. indet., Fombuena. G. *Heterotrypa* sp., Fombuena. H. *Trematopora acanthostylita*, Fombuena.

are bafflestones with *in situ* preserved sessile biota and stromatactoid-rich cementstones. Mud-mound complexes developed at various sites on an outer ramp, being influenced by weak to moderate wave and storm activity. The small size of the mounds and the geometry of the mound complexes reflect a limited accommodation space (Villas *et al.*, 2011). The mud-mound complexes pass shoreward to pelmatozoan-bryozoans meadows degraded by intense wave- and storm-induced processes (La Peña and Rebovilla members). Within these units pelmatozoan-rich packstones are frequent.

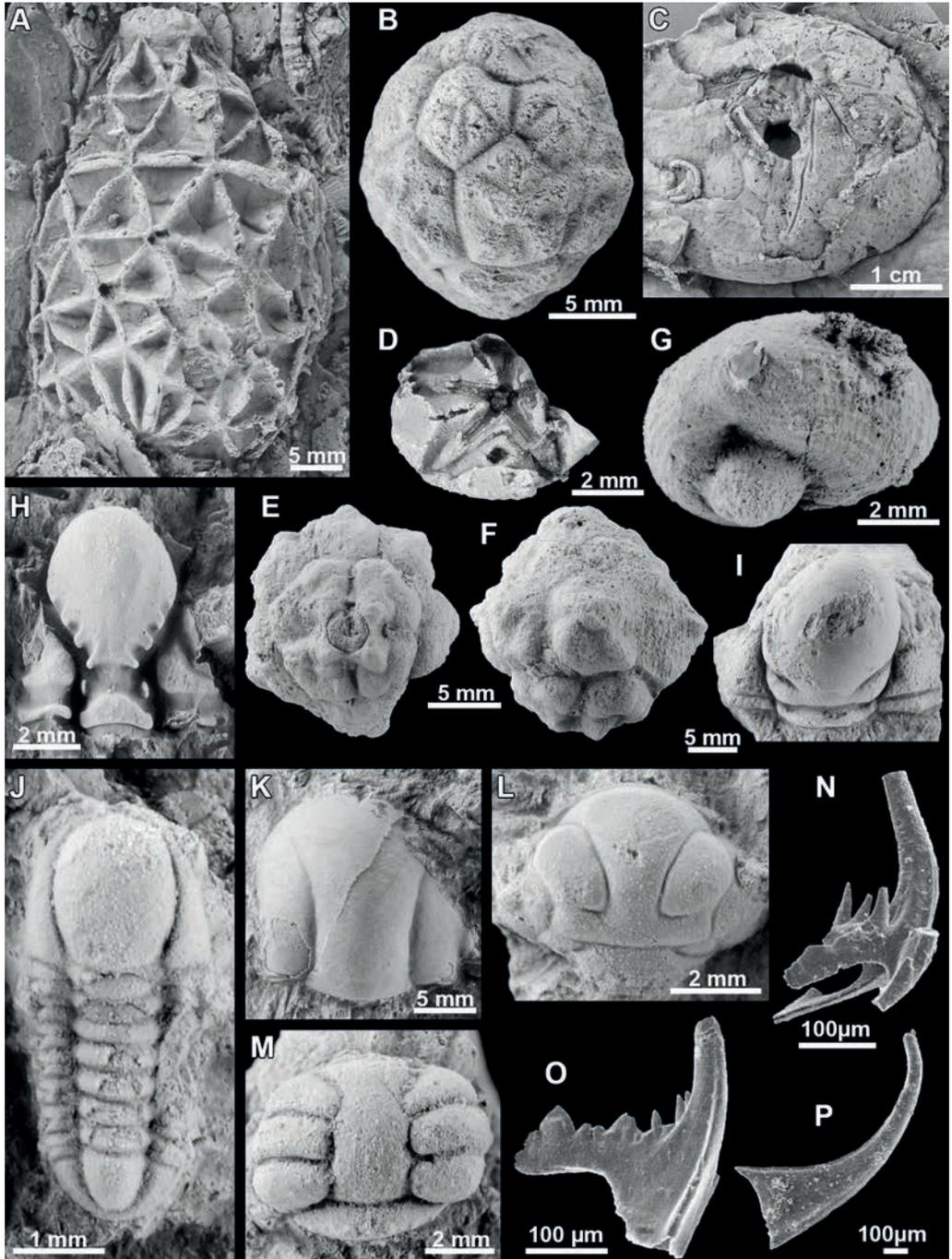
Conodonts characteristic of the *Amorphognathus ordovicicus* Zone (Figs. 13N, O, P) were identified by Carls (1975) throughout the massive limestones of the Rebollarejo Member. All the conodont taxa reported by Carls were reinterpreted by Sarmiento (1993) in terms of multielemental taxonomy. Sarmiento (2002) and Del Moral González (2008) brought new data and summarized the main features of the association.

The Cystoid Limestone Formation is very fossiliferous and contains (in order of abundance), bryozoans (Fig. 12), echinoderms (Fig 13A-F), brachiopods, ostracods, neritomorph gastropods (Figs. 13G), trilobites (Fig 13H-M), cephalopods and machaeridians (Hammann, 1992). From these groups, echinoderms (Chauvel *et al.* 1975; Chauvel and Le Menn, 1979), brachiopods (Villas, 1985), trilobites (Hammann, 1992) and bryozoans (Jiménez-Sánchez, 2009, 2010; Jiménez-Sánchez and Villas 2010) have been described in detail, whereas the others are in need of detailed study.

Echinoderms from the Cystoid Limestone Formation in the Peña del Tormo section are very abundant and well preserved in the lower La Peña Member. The most comprehensive papers on the echinoderms from these levels were published by Chauvel *et al.* (1975) and Chauvel and Le Menn (1979), who reported a diversified fauna of rhombiferans (*Corylocrinus melendezi*, *Juglandocrinus sdzuy* (Fig. 13B), *Caryocrinites elongatus*, *Caryocrinites cf. crassus*, *Caryocrinites europaeus*, *Caryocrinites* sp. (Figs. 13E-F), *Stichocystis unilineata*, *Heliocrinites cf. rouvillei* (Fig. 13A), *Heliocrinites minuta*, *Heliocrinites helmhackeri*, *Heliocrinites cf. saenzi*), diploporans (*Eucystis cf. angelini*, *Proteocystites hispanica* (Fig. 13C), coronoids (*Mespilocystites tregarvanicus* (Fig. 13D) and columnals belonging to several pelmatozoan genera (*Cylocharax paucicrenellatus*, *Malovicrinus* sp., *Ristnacrinus cf. cirrifer*, *Conspectocrinus cf. celticus*).

Trilobites are very diverse and exhibit a mixture of genera which persisted from the long established *Selenopeltis* Province of the North African shelf of Gondwana, but includes others with Baltic, Laurentian or Chinese origins (Hammann, 1992). The appearance of these trilobites and the increased diversity are related to the Boda global warming event (Fortey and Cocks, 2005). Among the endemic representatives are *Selenopeltis*, *Hispaniaspis*, *Nobiliasaphus*, *Cekovia* (Fig. 13K), *Zetillaenus*, *Dreyfussina*, *Radnorina*, *Lichas*, *Prionocheilus*, *Eccoptochile*, *Actinopeltis* and possibly *Ulugtella*. Baltic influence is represented by *Stenopareia?*, *Parillaenus?*, *Rorringtonia*, *Harpidella*, *Panarchaegonus*, *Dicranopeltis* (Fig. 13L), *Josephulus?* and *Ceraurinus?*. Typical Laurentian trilobites are *Amphoriops*, *Holdenia* (Fig. 13J), *Heliomeroides*

Figure 13. Common echinoderms, trilobites and conodonts from the Cystoid Limestone Formation. A. Lateral view of *Heliocrinites cf. rouvillei*. B. Lateral view of a complete crown of *Juglandocrinus sdzuyi*. C. Oral view of *Proteocystites hispanica* showing diplopores, food grooves and facets for brachioles insertion. D. Oral view of *Mespilocystites tregarvanicus*. E-F. Lateral (F) and aboral (F) views of *Caryocrinites* sp. G. Gastropod (*Neritomorpha* indet.). H. *Ovalocephalus cf. tetrasulcatus*, internal mould of cranium in dorsal view. I. Cranium of *Eccoptochile nullicauda*. J. Complete specimen of *Holdenia insculpta*. K. Cranium of *Cekovia perplexa perplexa*. L. Cranium of *Dicranopeltis polytoma*. M. Cranium of *Heliomera (Heliomera) crassilobata*. N-P. Conodonts of the *Amorphognathus ordovicicus* zone. N. *Amorphognathus ordovicicus* Branson and Mehl, Sd element in lateral view. O. *Hamarodus europaeus*, Sa element in lateral view. P. *Scabbardella altipes*, inner lateral view of a right drepanodiform element. Specimens A, C, D are latex casts.



(Fig. 13M), *Calipermurus?* and *Diacanthaspis*. Trilobites with a putative Chinese origin include *Lamproscutellum*, *Ovalocephalus* (Fig. 13H), and *Sinocybele*. Although bearing some taxa considered to have originated in other regions, the trilobite assemblage of the Cystoid Limestone are still composed largely of hitherto endemic representatives. Some of these Gondwanan trilobites also expanded their geographical distribution to other realms during the Boda Event (Colmenar *et al.*, 2017).

Brachiopod diversity (up to 28 different taxa) is significantly higher than in the underlying siliciclastic formations. The brachiopods found in the La Peña Member are elements of the *Nicolella* Community including *Orbiculoidea* sp., *Eoplectodonta* (*Kozlowskites*) sp., *Leangella anaelyta* (Figs. 9I–J), *Aegironetes* sp., *Leptestiina prantli*, *Kjaerina* (*Kjaerina*) sp., *Iberomena sardoa*, *Leptaena* sp., *Oxoplecia luesmae*, *Triplesia* cf. *cymbula*, *Nicolella actoniae* (Fig. 9K–L), *Dolerorthis* sp., *Schizophorella* sp., *Plaesiomys* sp., *Dalmanella* sp., *Portranella* sp., *Eridorthis angustisulcata*, *Skenidioides* cf. *paucicostatus*, *Ptychopleurella villasi*, *Mcewanella barroisi*, *Epitomyonia* sp., *Saukrodyctia reticula*, *Porambonites* (*Porambonites*) *magnus* (Fig. 9G–H), *Eoanastrophia pentamera* (Fig. 9D–E) and *Rostricellula termieri* (Villas, 1985; Mélou, 1990). Brachiopods were strongly controlled by environmental conditions (Colmenar *et al.*, 2014) and were consequently very sensitive to changes in the environmental parameters of their habitat. The low diversity brachiopod associations, endemic to the Mediterranean region during the early Late Ordovician, were replaced by immigrants (*Nicolella* Community) from low latitude palaeocontinents (Baltica-Avalonia), better adapted to the environmental changes accompanying the Boda event (e.g., switch to carbonate deposition, increase of sea temperatures). Larvae of these organisms arrived to the Mediterranean region presumably favoured by the eastward and poleward warm-water currents of the temperate latitude. Once settled there, this immigrant fauna occupied new niches, displacing the endemic Mediterranean faunas to occupy a more marginal role in the association and eventually driving them to extinction (Colmenar, 2015).

The Cystoid Limestone represents the highest Ordovician diversity of trilobites and brachiopods in the study area, but in terms of the echinoderm fauna there is an important switch in the taxonomic faunas from the underlying Fombuena Formation to the Cystoid Limestone. This could be also related to the immigration of faunas from higher latitudes as has been explained for brachiopods and trilobites, but the type of substrate and the more energetic conditions in the Cystoid Limestone Formation were also important factors to explain changes in diversity and taxonomic composition.

STOP 2: Late Ordovician benthic communities from La Rebosilla section.

Location

This section is located in an arable land located about 1.5 km. South-West Luesma village, in a place so-called La Rebosilla (Fig. 14).

Coordinates: 41° 9' 28" N, 1° 9' 40" W. Geological map of Spain, 1:50000, sheet of Moyuela (466).

Geological setting: Herrera Unit (Eastern Iberian Chain).

Lithostratigraphical unit: Cystoid Limestone Formation (eastern facies, Rebosilla and Ocino members).

Age: Katian 3–4 (Late Ordovician).

Aims

Look at the invertebrate faunas from the Cystoid Limestone in the eastern facies and comparing with those from the western facies.

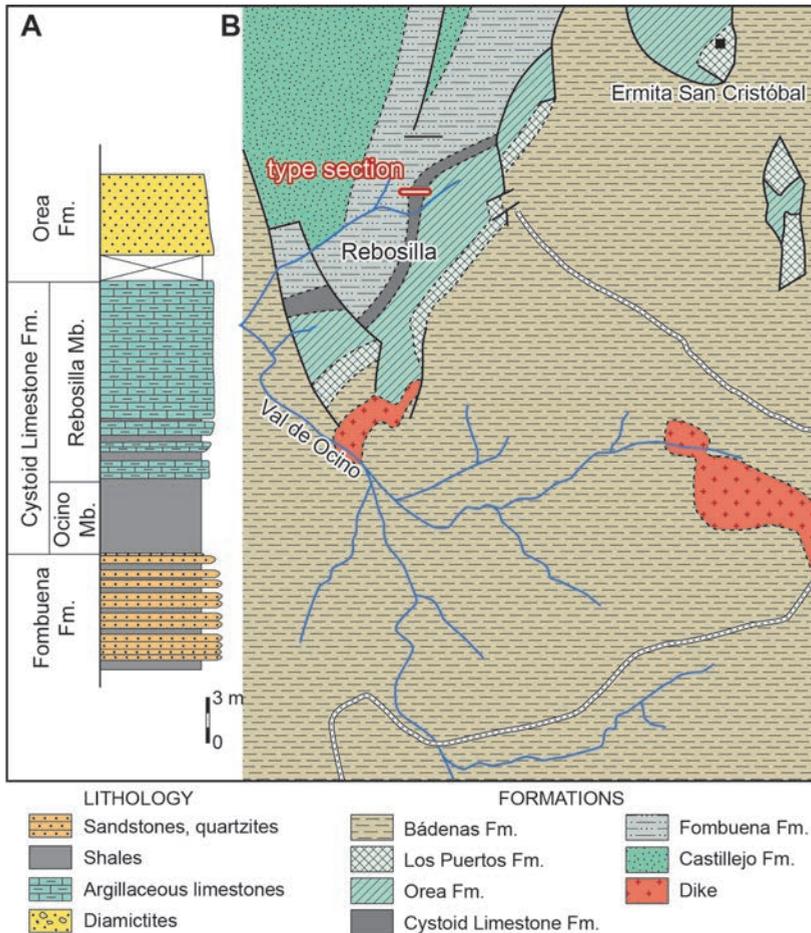


Figure 14. Geological map and lithological column of the La Rebosilla locality. Modified from Hammann (1992). Type section indicated with a red line.

Description

Moving eastwards from the former locality, the Cystoid Limestone Formation displays its typical proximal facies associations (Fig. 15). It is characterized by basal calcareous siltstones to claystones, up to 5 m thick, known as the Ocino Member, and alternating marly shales and limestones, nearly 20 m thick, above them. This upper part of the unit is known as the Rebosilla Member, which is considered to represent the same environmental setting than that of the La Peña Member, visited in the previous stop (Fig. 4).

A taphonomic study of skeletons by Vennin *et al.* (1998) showed vertical changes on a decimetre-scale, where erosive bases are paved by abraded shell layers that pass gradually upward into skeletal elements that show a greater degree of articulation and larger size. Complete articulated skeletons of pelmatozoans and fragile dendroid/ramose bryozoans overlie these storm-induced deposits and are

interpreted to represent quiet episodes that favoured episodic development of pelmatozoan and bryozoan meadows. Therefore, sediments of the Rebovilla Member can be attributed to open-sea conditions in an offshore environment, which experienced quiet deposition punctuated by storm events.

The first fossils from this log were reported by Dereims (1898), who compared the fauna with "*Orthis*" *actoniae* and cystoids (*Echinospaerites*, *Caryocrinites*) with that of the Upper Ordovician described

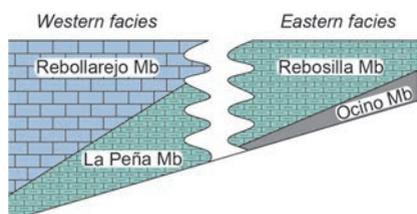


Figure 15. Relationship of facies and lithostratigraphic units of the Cystoid limestone Formation in the eastern Iberian Chain. Modified from Hammann (1992).

by v. Koenen (1886) from the Montagne Noire (France). Meléndez (1944a, 1944b, 1959) and Meléndez and Hevia (1947) offered the first descriptions of echinoderms from La Rebovilla section and considered them Ashgillian in age. The most recent compilations of those faunas come from Chauvel *et al.* (1975) and Chauvel and Le Menn (1979), who provided several species of rhombiferans (*Cariocystites* sp., *Cariocystites?* *saenzi*, *Heliocrinites* cf. *rouvillei*, *Heliocrinites* aff. *helmackeri*, *Heliocrinites* *pacheco*) and isolated columnals (*Conspectocrinus celticus*, *Ristnacrinus* cf. *cirrifer*, *Cylocharax paucicrenullatus*, *Trigonocyclicus* cf. *vajgatchensis*, *Aonodiscus spinosus*).

All the studied specimens from this section come from the Rebovilla Member and can be collected as moulds from weathered and decalcified carbonate beds (Fig. 14). The echinoderm faunas from the Cystoid Limestone need a revision because some genera (e.g. *Caryocrinites*, *Heliocrinites*) include several species based on poorly preserved specimens or discrete morphological characters. Some of the differences between species are better explained in terms of ontogenetic development, intraspecific variation and taphonomic constraints. Brachiopods from this locality coincide with those taxa typical of the *Nicolella* Community, listed from the La Peña Member in the former stop. Colmenar *et al.* (2013) assigned this community to the Benthic Assemblage 3, developed in an offshore sedimentary environment, above the lower limit for active photosynthesis. They concluded that the *Nicolella* Community was adjacent to the *S. havliceki* Community, on its seaward side, during the first pulses of the Boda event.

STOP 3: Invertebrate faunas from the Bádenas Formation

Location

This section is located in a small hill about 1.7 km South-East Luesma village, in a place so-called Las Bruterías.

Coordinates: 41°9'25"N, 1°7'47"W.

Geological map of Spain, 1:50,000, sheet of Moyuela (466).

Geological setting: Herrera Unit (Eastern Iberian Chain).

Lithostratigraphical unit: Bádenas Formation, s3d member (Fig. 16).

Age: Ludlow (Silurian).

Aims

Visit one of the few Silurian outcrops in Spain that has provided abundant complete crinoids and brachiopods. Look at the different sedimentary structures associated with the fossiliferous beds. Discuss the possible environment based on fossil preservation and sedimentary structures.

Description

As stated above, the Ordovician-Silurian boundary in the Iberian Cordillera lies in the uppermost quartzites of the Los Puertos Formation (20–40 m), where recent sampling has resulted in the discovery of some brachiopods (*Plectothyrella crassicosta chauveli* and *Eostropheodonta* sp.) typical of the *Hirnantia* Fauna. The overlying Bádenas Formation comprises mostly shales with scattered sandstone intercalations (900–1400 m). Carls (1965) studied the stratigraphy of this formation and subdivided it into five members, from s3a to s3e: s3a, s3c and s3e are mostly composed of shales while the other two members (s3b, s3d) are mostly quartzitic. The s3d member close to Luesma is approximately 43 m thick (Carls, 1965), very fossiliferous and contains a rich assemblage dominated by chonetid and rhynchonellid brachiopods, gastropods, bivalves, trilobites, tentaculitoids and echinoderms (Figs. 17–18). These faunas have not yet been studied in detail.

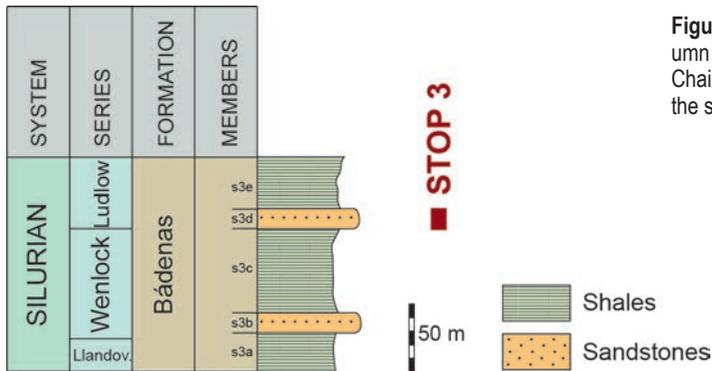
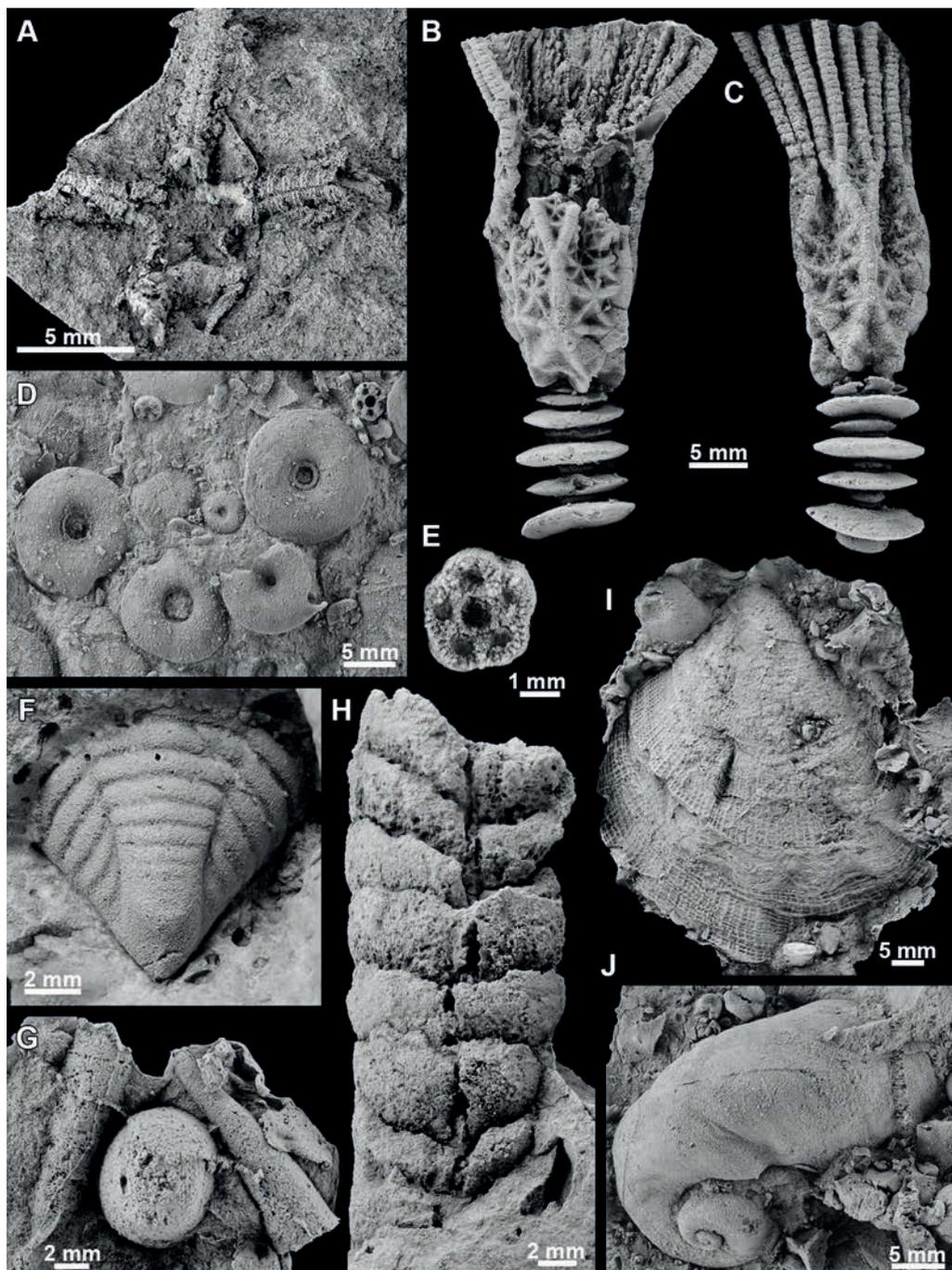


Figure 16. Schematic stratigraphic column of the Silurian of the Eastern Iberian Chain. Note the stratigraphic position of the stop.

The black shales of the Bádenas Formation in the eastern Iberian Chain have provided abundant graptolites indicating that the formation extends from the basal Telychian *Rastrites linnaei* [= *Spirograptus guerichi*] Zone up to the basal Ludfordian *Saetograptus leintwardinensis* Zone (Gutiérrez-Marco and Štorch, 1998). The black shales and nodules also contain brachiopods, bivalves, cephalopods, eurypterids, phyllocarids, tentaculitids, trilobites and conodonts. Thin sandstone beds of the upper part of the formation have yielded shallow-water brachiopods, echinoderms, molluscs, conodonts and trilobites (Carls, 1974; Gandl, 1972; Sarmiento *et al.*, 1998; Le Menn *et al.*, 2003). The Bádenas Formation is overlain by the Luesma Formation, a sandstone-dominant unit about 200 m thick that towards its upper part has provided successive assemblages of Pridoli brachiopods and Lochkovian conodonts and brachiopods (Carls, 1977).

The lower member (s3a) of the Bádenas Formation (Fig. 16) has yielded a fossil record that occurs in two distinct levels of sandstone and quartzitic beds intercalated within this shale dominated member. The lowest stratigraphically and thus, oldest coquina, has provided a low diversity brachiopod assemblage, with only four taxa identified. It is dominated by dalmanellids such as *Mendacella* sp. and Dalmanellidae indet., as well as by the primitive leptostrophiid *Viodostrophia alcaldei*. Also some scarce specimens of an undetermined camarotoechiid occur.

The second assemblage occurring in this member is more diverse than the former, with up to 8 brachiopod taxa identified. *Viodostrophia alcaldei* and *Mendacella* sp. are still very common here as well as *Platyorthis* sp. Other relevant brachiopod occurrences are *Howellella* sp., *Athyris* sp. and an indeterminate strophomenoid. Other fossil groups such as crinoids, trilobites and bivalves are also represented in these



coquinoid levels. There is not an accessible complete stratigraphic section of these levels, but it is possible collecting abundant samples from the quartzitic boulders accumulated in a crop field by farmers.

The low diversity of the former assemblages may be explained by the likely extreme ecological conditions in the epicontinental seas, during the Ordovician-Silurian transition, after the melting of the Hirnantian ice caps, the sharp drowning of marine platforms and the stratification of ocean waters. As a result of these conditions lower Silurian benthic faunas are very rare in south and central Europe, largely because rocks of this age, although widespread, are part of a vast mass on the margin of the Gondwanan continent affected by anoxia, in which only graptolites, bivalves and cephalopods are usually found (Cocks and Fortey, 1988; Villas and Cocks, 1996). This mass extended over present-day North Africa, through the Iberian Peninsula, Sardinia and Italy as far north as Bohemia. Development of benthic shelly communities were limited to areas with volcanic activity where water could become oxygenated enough to support benthos, as in the associations recorded from the Zekovice Formation in Bohemia (Havlíček and Štorch, 1990) and from the volcanoclastic top of the El Castro Formation, cropping out on the North Spanish Asturian coast (Villas and Cocks, 1996). The peculiarity of the Bádenas Formation benthic associations is that they are related to a very shallow sea, with sandy level bottom at the margin of the emerged Cantabrian-Ebroan Massif, oxygenated enough to support benthic life. In spite of the differences among the Early Silurian north Spain volcanic mounds and the Iberian sandy level bottom, the brachiopod communities that they supported share a similar low diversity, with some common species, as the primitive leptostrophiid *Viodostrophia alcaldei*.

After the rare records of graptolites (Wehner, 1984) and by correlation with laterally equivalent levels from the western Iberian Chain, dated by means of graptolites (Gutiérrez-Marco and Štorch, 1998), we have attributed to the basal s3a Member of the Bádenas Formation a Telychian (Llandovery) age.

The s3d member of the Bádenas Formation, close to Luesma village, is approximately 43 m thick (Carls, 1965). Las Bruterías locality is especially fossiliferous containing a rich assemblage dominated by chonetid and rhynchonellid brachiopods, gastropods (Fig. 17J), bivalves (Fig. 17I), trilobites, tentaculitoids, cephalopods (Figs. 17G–H) and echinoderms (crinoids and ophiuroids; Le Menn *et al.*, 2003; Zamora *et al.*, 2015). This locality is the one that we are going to sample in this stop.

From these levels Carls (1974) described the proschizophoriid *Baturria edgelliana simonae* (Figs. 18A–F) and Racheboeuf (1981) *Strophochonetes* (*Strophochonetes*) *bassetti* (Fig. 18J); the rhynchonellid *Camarotoechia* sp. (Figs. 18G–I) occurs besides them.

Crinoids, especially *Dimerocrinites aragonensis* (Figs. 17B–D), are concentrated in some layers; although there are isolated columnals from other species of crinoids (Fig. 17E) and rare ophiuroids (Fig. 17A). Le Menn (1985) was the first that mentioned *Dimerocrinites* in those levels, although it was not until 2003 when he described *Dimerocrinites aragonensis* Le Menn (in Le Menn *et al.* 2003). *Dimerocrinites* has a heteromorphic stem composed of extremely large nodals and small internodals, associated with large articular facets (Fig. 17D). The Iberian species share global affinities with several species from the Silurian of Gotland, Wales and New York (Le Menn *et al.*, 2003). Few scarce trilobite remains have been also found and belong to genus *Homalonotus* (Fig. 17F).

Conodonts have been reported from s3d quartzitic member of the Bádenas Fm. suggesting an undetermined late Wenlock-early Ludlow (Homerian to Gorstian) age (García López *et al.*, 1996).

Figure 17. Common echinoderms, trilobites, cephalopods, bivalves and gastropods from the s3d Member of the Bádenas Formation, upper Wenlock-lower Ludlow (Silurian). A. indeterminate ophiuroid. B–C. The crinoid *Dimerocrinites aragonensis*. D–E. Crinoid columnals of at least two different taxa, *D. aragonensis* and an indeterminate crinoid. F. pygidium of the trilobite *Homalonotus* sp. G–H. Cephalopods indet. I. Bivalve indet. J. unidentified neritomorph gastropod. Specimens A–E, G, I, J are latex casts.

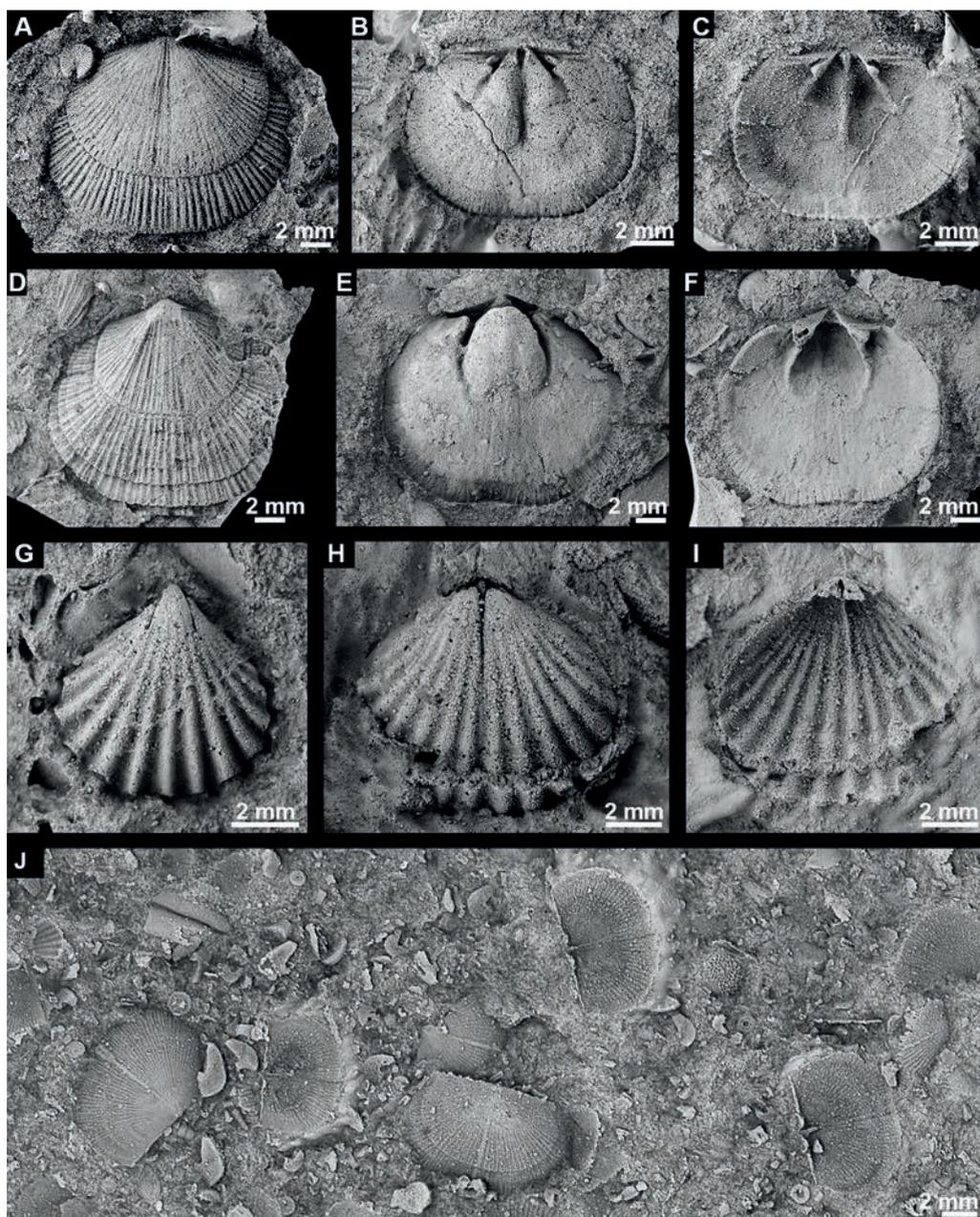


Figure 18. Brachiopods from the s3d Member of the Bâdenas Formation, upper Wenlock-lower Ludlow (Silurian). A-F. *Baturria edgelliana simonae*, latex cast of exterior of a dorsal valve (A), internal mould (B) and latex cast of interior (C) of dorsal valve, latex cast of exterior of ventral valve (D), and internal mould (E) and latex cast of interior (F) of ventral valve. G-I. *Camarotoechia* sp., internal mould of ventral valve (G), internal mould (H) and latex cast of interior (I) of dorsal valve. J. *Strophochonetes* (*Strophochonetes*) *bassetti*, latex cast of a rock slab with moulds of several disarticulated valves.

DAY 2: December 16th 2019

**CAMBRIAN INVERTEBRATE FAUNAS FROM THE BADULES UNIT:
PURUJOSA AND MURERO LOCALITIES**

Samuel Zamora, J. Javier Álvaro, Jorge Esteve and Stephen Pates

INTRODUCTION

The pre-Variscan exposures of the Iberian Massif have been traditionally subdivided into four main tectonostratigraphic units, known as the Cantabrian, West Asturian-Leonese, Central-Iberian and Ossa-Morena zones (Fig. 19). These “zones”, though representing Variscan differences in deformation style and igneous record, are commonly used in pre-Variscan palaeogeographic reconstructions. During Cambrian times, the Ossa-Morena Zone recorded the main axis of a rifting transect that was connected with Morocco and formed the so-called Atlas/Ossa-Morena Rift (Álvaro *et al.*, 2014). Between the Ossa-Morena rifting axis and the Gondwana coastline was located a peri-Gondwanan basin (named Cantabro-Iberian Basin in some works) that virtually behaved as a Cambrian volcanic-poor, passive margin (see details in Sánchez-García *et al.*, 2019). The latter basin was limited to the NE by the Cantabro-Ebroan Land area (an edge of Gondwana), at present covered by the Cenozoic Ebro Basin. The southeastern prolongation of the West Asturian-Leonese/Cantabrian contact is represented by the Anguiano Thrust (limiting the Demanda Massif to the NE) and the Datos Fault (crosscutting longitudinally the eastern Iberian Chain; Álvaro *et al.*, 2018). From a structural point of view, mainly controlled by Variscan deformation, the Iberian Chains can be subdivided into the Badules, Mesones and Herrera units, respectively separated by the Jarque and Datos faults.

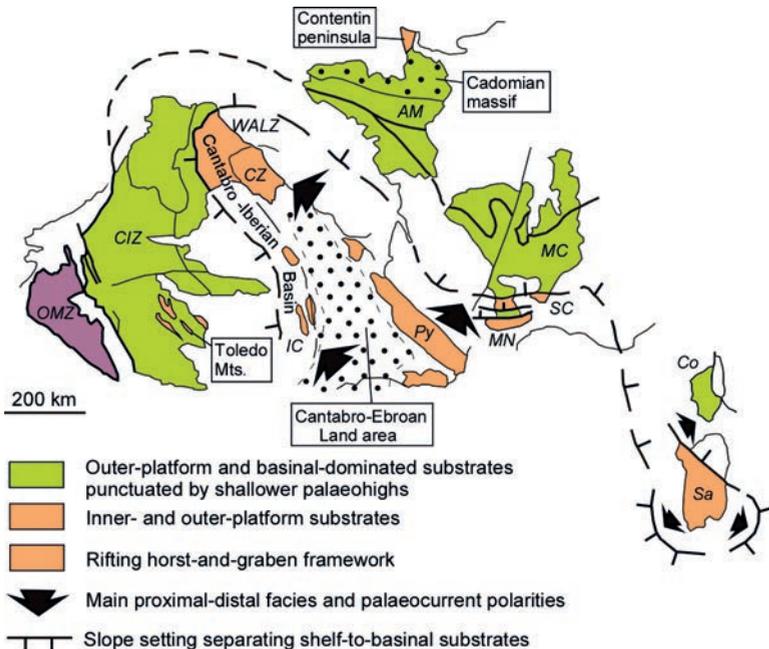


Figure 19. Tentative Cambrian palaeogeographic reconstruction of the inner- platform / basin transects through the SW-European margin of West Gondwana; modified from Álvaro *et al.* (2010): OMZ, Ossa-Morena Zone; CIZ, Central-Iberian Zone; IC, Iberian Chains; D, Sierra de la Demanda; CZ, Cantabrian Zone; WALZ, West-Asturian Leonese Zone; AM, American massif; MC, Massif Central; SC, Southern Cévennes; MN, Montagne Noire; Py, Pyrenees.

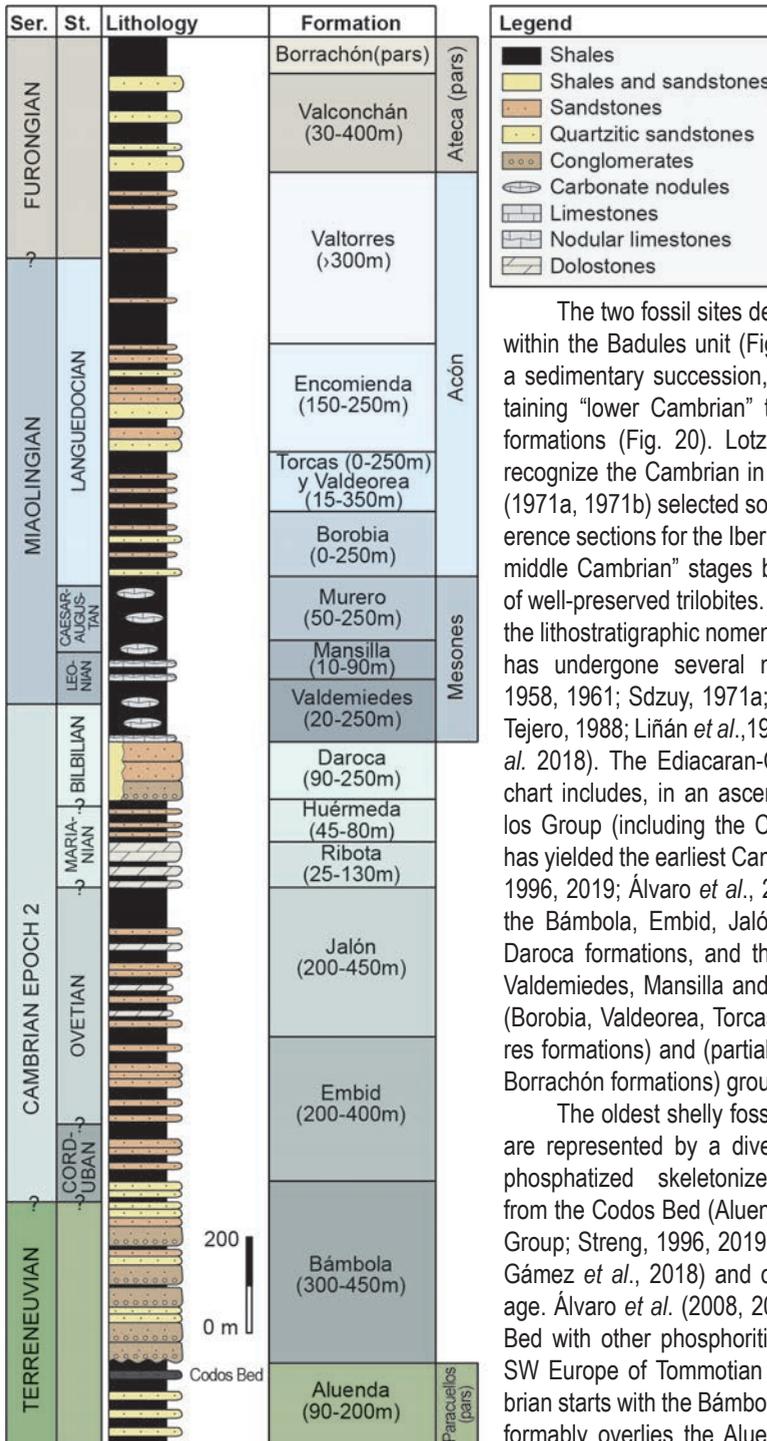


Figure 20. Synthetic stratigraphic log of Cambrian rocks in the Iberian Chains.

The two fossil sites described below are situated within the Badules unit (Fig. 1). The latter comprises a sedimentary succession, about 3000 m thick, containing “lower Cambrian” to Furongian volcanic-free formations (Fig. 20). Lotze (1929) was the first to recognize the Cambrian in the Iberian Chains. Sdzuy (1971a, 1971b) selected some of their localities as reference sections for the Iberian (so regional) “lower and middle Cambrian” stages because of the abundance of well-preserved trilobites. Since Lotze’s (1929) work, the lithostratigraphic nomenclature for Cambrian rocks has undergone several modifications (e.g., Lotze, 1958, 1961; Sdzuy, 1971a; Schmitz, 1971; Liñán and Tejero, 1988; Liñán *et al.*, 1992; Álvaro, 1995; Gámez *et al.* 2018). The Ediacaran-Cambrian lithostratigraphic chart includes, in an ascending order: the Paracuellos Group (including the Codos phosphatic Bed that has yielded the earliest Cambrian microfossils; Streng, 1996, 2019; Álvaro *et al.*, 2016; Gámez *et al.*, 2018), the Bámbola, Embid, Jalón, Ribota, Huérmeda and Daroca formations, and the Mesones (including the Valdemiedes, Mansilla and Murero formations), Acón (Borobia, Valdeorea, Torcas, Encomienda and Valtorres formations) and (partially) Ateca (Valconchán and Borrachón formations) groups (Fig. 20).

The oldest shelly fossils from the Iberian Chains are represented by a diverse shelly assemblage of phosphatized skeletonized microfossils collected from the Codos Bed (Aluenda Formation; Paracuellos Group; Streng, 1996, 2019; Álvaro *et al.*, 2008, 2016; Gámez *et al.*, 2018) and considered as Fortunian in age. Álvaro *et al.* (2008, 2016), correlated the Codos Bed with other phosphoritic units from Morocco and SW Europe of Tommotian age. The traditional Cambrian starts with the Bámbola Formation, which unconformably overlies the Aluenda Formation and repre-

sents the post-Cadomian beginning of rifting conditions (Álvarez *et al.*, 2008). The Bámbola Formation is a conglomeratic-dominant unit grading upsection into quartzitic strata, the uppermost part of which has yielded a rich assemblage of Terreneuvian arthropod ichnofossils such as *Monomorphichnus lineatus*, *Rusophycus cantabricus* (= *R. bonnarensis*) and *R. fasciculatus* (= *R. avalonensis*) (*sensu* Gámez *et al.*, 2018). The overlying sandstone/shale alternations of the Embid Formation also contain a rich ichnological record including the first records of *Cruziana* and *Astropolichnus hispanicus* (Álvarez *et al.*, 1993a; Pillola *et al.*, 1995). The oldest trilobites from the Iberian Chains are located in the shales of the heterolithic Jalón Formation, rich in dolostone interbeds with halite and gypsum pseudomorphs (Álvarez *et al.*, 1995, 2000), where Szalay (1987) described *Dolerolenus?* sp. indet., *Anadoxides?* sp. indet and *Thoralaspis* n. sp., indicating a Cambrian Epoch 2 (regional Ovetian) age. Details of the overlying formations are given below for their respective stops. Complete lists of formations and fossil content have been provided in several fields-trip guides and do not need to be repeated herein (e.g., Liñán *et al.*, 2008).

During the field excursion, we will have the opportunity to visit two localities of the Badules unit: Purujosa (northern edge of the eastern Iberian Chains) and Murero (western Iberian Chain). The former contains a stratigraphic section that spans from the Embid to the Valtorres formations with fossiliferous levels in several intervals (stops 4-10). The classic locality of Murero records a stratigraphic interval that spans from the top of the Valdemedes Formation to the base of the Borobia Formation in a continuous section located along the Rambla de Valdemedes (stop 11).

CAMBRIAN OF PURUJOSA

The Cambrian of Purujosa is located in the northernmost part of the eastern Iberian Chain, within the Tablado Mountain (Fig. 21). In this area, the Jarque Fault is locally named the Tablado Fault and separates the Cambrian outcrops from a Triassic Depression. The Cambrian strata comprise an almost continuous section from the topmost part of the Embid Formation to the Valtorres Formation. Probably because of its tough accessibility, this locality was unnoticed by early workers. Fossils from Purujosa were first mentioned by Samaniego *et al.* (1972) who described a trilobite assemblage from the lower Cambrian Ribota Formation. Quarch (1967) recorded the presence of *Lusatiops ribotanus* in the Huérmeda Formation, and a rich assemblage of trilobites in the Mesones Group including typical paradoxidids and agraulids. Zamora (2005) was the first to make a detailed mapping of the area, alongside a stratigraphic study, and highlighted the potential of this locality for future research. A complete description of the echinoderm faunas occurs in Zamora's (2009) PhD, while the systematics of trilobites from the Murero Formation was made by Esteve (2011). The fossil record from Purujosa has been considered key to understand several aspects for echinoderm evolution (Rahman and Zamora, 2009; Zamora *et al.*, 2009, 2012, 2013; Zamora, 2010; Zamora and Smith, 2008, 2010, 2012), trilobite enrolment (Esteve *et al.*, 2010, 2011, 2013, 2017), trilobite systematics (Esteve, 2014; Esteve *et al.*, 2012; Álvarez *et al.*, 2013a), and predator-prey interactions (Zamora *et al.*, 2011; Pates *et al.*, 2017).

Several aspects of the Purujosa area will be examined. After a general introduction of the geological setting from a panoramic view (stop 4), we will visit the faulted Cambrian/Mesozoic contact, the so-called Jarque Fault, followed by a short stop to recognize the Ribota Formation and its trilobite content (stop 5). The Mesones Group is probably the most fossiliferous and interesting interval from the whole Cambrian: we will visit the Valdemedes Formation, poorly documented in this area (stop 6); the Mansilla Formation that records a rich record of trilobites and echinoderms (stop 7); and the Murero Formation (stops 8, 9). This will be followed by a short stop in the Valtorres Formation to look at siliceous concretions with three dimensionally preserved shelly fossils of Guzhangian age (stop 10). On the journey back to Daroca, we plan a short stop in the classic locality of Murero (stop 11) to visit levels of exceptional preservation.

STOP 4: Panoramic view of the Purujosa area within the Moncayo Natural Park**Location**

La Crucija high (1000 m). Road that connects Oseja with Calcena (Fig. 21).

Coordinates: 41°37'15.67"N, 1°42'59.88"W. Geological map of Spain, 1:50000, sheet of Illueca (381).

Aims

Show a panoramic view of the Cambrian rocks from Purujosa and neighbouring Mesozoic outcrops. Look at the faulted contact through the Jarque (or Tablado) Fault separating the Palaeozoic and Mesozoic.

Description

The Jarque Fault is one of the main structures involved in the evolution of the eastern Iberian Chain. It is locally known as the Jarque-Tablado Fault (Fig. 21), displays a NW-SE trending, and extends longitudinally for at least 50 km. Recent results obtained from anisotropy of magnetic susceptibility (AMS) indicate a structure resulting from the reactivation of an ancient (late Variscan to Triassic) fault during the Alpine Orogeny associated with the NNE-SSW compression (Sierra *et al.*, 2019).

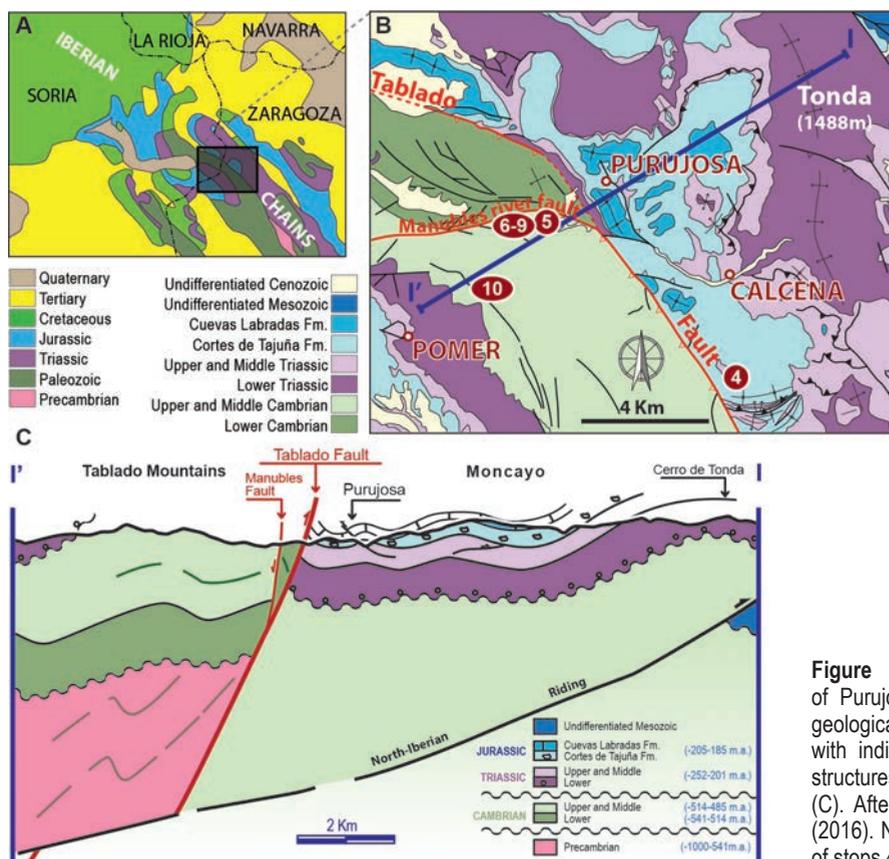


Figure 21. Location of Purujosa (A, B) and geological cross section with indication of major structures in the area (C). After Zamora *et al.* (2016). Note the position of stops 4 to 10.

STOP 5: Trilobites from the lower Cambrian Ribota Formation

Location

Path crossing the Isuela river in the SW of Purujosa. Section between the Cabecillo hill and Parideras del Prado (Fig. 22).

Coordinates: 41°40'34,39"N, 1°46'40,68"W

Geological map of Spain, 1:50.000, sheet of Tabuena (352).

Geological setting: Badules Unit (eastern Iberian Chain).

Lithostratigraphic unit: Ribota Formation.

Age: Cambrian Series 2-Stage 4 (regional Marianian stage).

Aims

Look at fossil faunas and lithology of the low diversity fossiliferous Cambrian Series 2 Ribota Formation. Discuss the origin of dolomitization of carbonate banks.

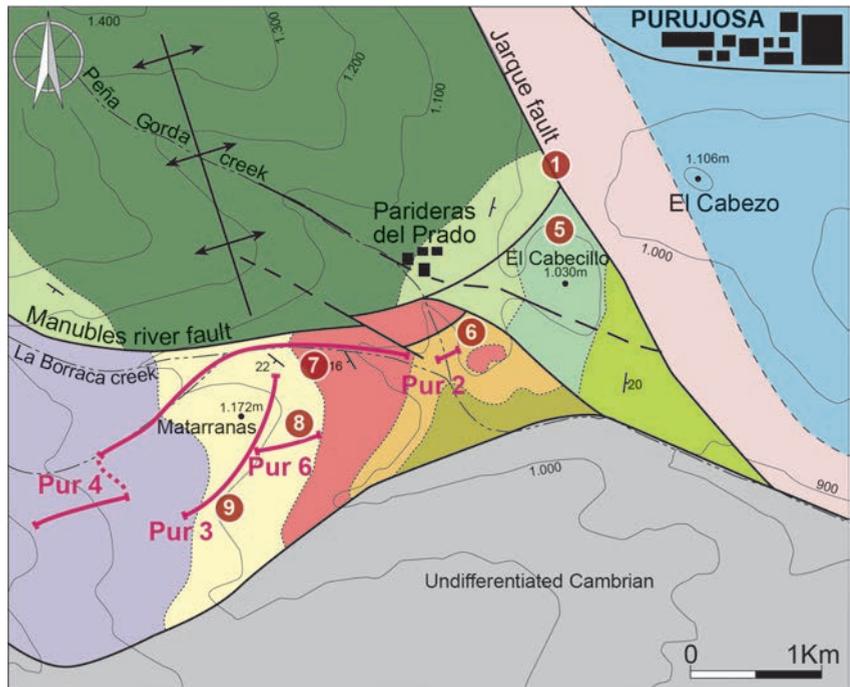


Figure 22. Detailed geological map of the Purujosa area with location of visited sections and situation of stops; modified from Zamora (2005).

Description

This outcrop provides one of the few places in the Iberian Chains where the Ribota Formation yields abundant and well-preserved trilobites (Fig. 23). The Ribota Formation is locally a 115 m-thick succession composed of yellow-grey dolostones with interbedded shales. Dolomitization is both syndimentary (related to evaporitic conditions, indicated by the common presence of gypsum and halite pseudomorphs, in a sabkha depositional environment recording episodic subaerial exposure and tepee and mud-crack development) and Variscan (fault-related; Álvaro *et al.*, 1995) in origin. Shale interbeds contain mainly trilobites, brachiopods, hyoliths and trace fossils. Two trilobite assemblages are recognized: (i) the lower one is characterised by dark-purple shales with abundant *Lusatiops ribotanus*; whereas (ii) the upper assemblage is more diverse and contains *L. ribotanus*, *Strenuaeva incondita* and *Kingaspis (Kingaspidoidea) velata*, hyoliths and brachiopods. Other undetermined redlichiid trilobites have been found in neighbouring localities. The trilobite fauna suggests a Cambrian Age 3 (regional Marianian age), which broadly correlates with the Siberian Botoman Stage.

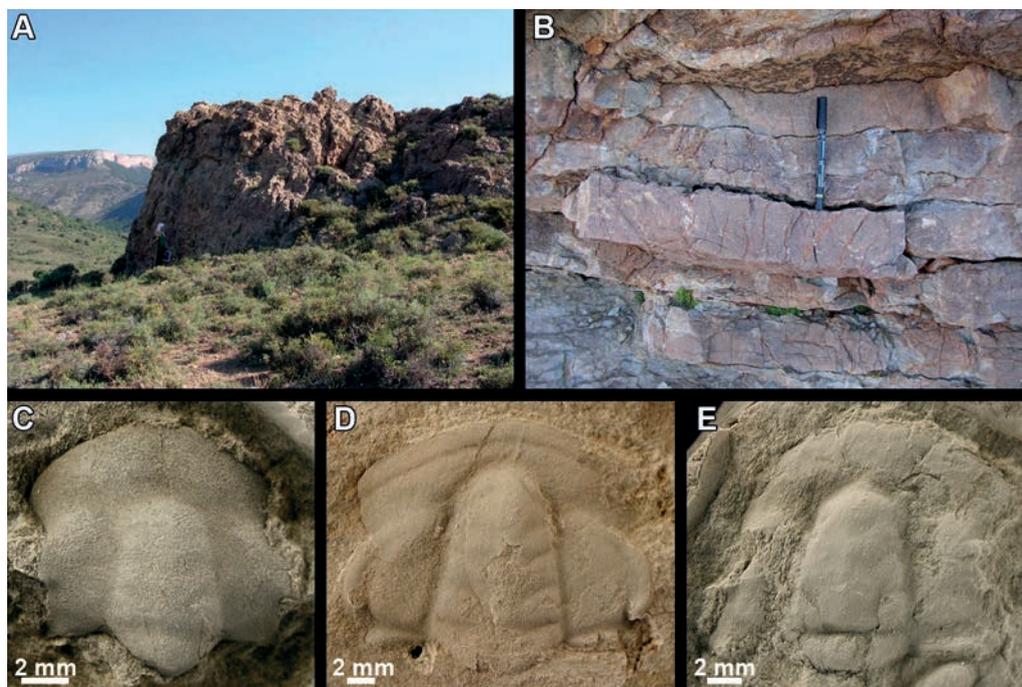


Figure 23. General aspects and fossils from the Ribota Formation. A. Dolostone massive levels. B. Detail of bedded dolostone. C. Cranium of *Kingaspis (Kingaspidoidea) velata*. D. *Lusatiops ribotanus*. E. *Strenuaeva incondita*.

STOP 6: Trilobites from the Valdemiedes Formation

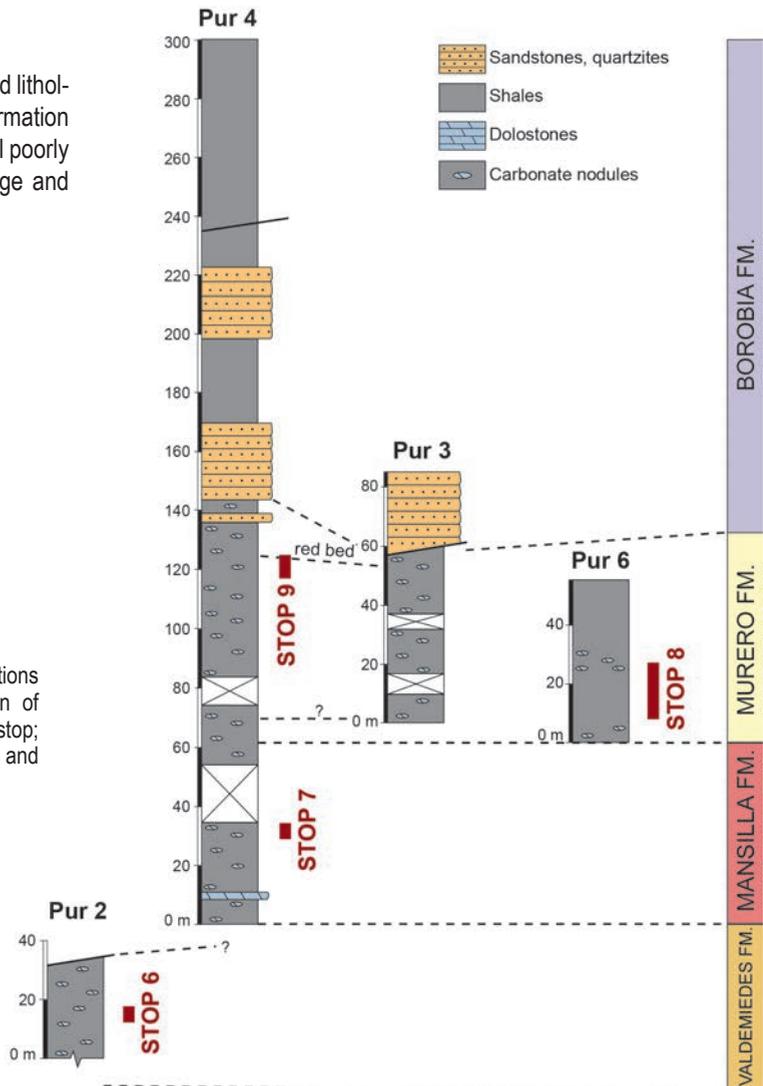
Location

La Borraca creek. Section Purujosa 2, located in the northern side of the creek (Figs. 22, 24).
 Coordinates: 41°40'12.06"N, 1°46'49.04"W
 Geological map of Spain, 1:50.000, sheet of Tabuena (352).
 Geological setting: Badules Unit (eastern Iberian Chain).
 Lithostratigraphic unit: Valdemiedes Formation.
 Age: Cambrian Series 2-Stage 4 (regional Bilbilian-Leonian).

Aims

Look at the faunas and lithology of the Valdemiedes Formation that preserve a rich, but still poorly studied, trilobite assemblage and carbonaceous algae.

Figure 24. Stratigraphic sections from Purujosa with indication of the intervals visited in each stop; modified from Zamora (2005) and Esteve (2011).



Description

The Valdemiedes Formation in the study area comprises a 45 m thick succession of shales with interbedded carbonate nodules (Fig. 25A). The best outcrops include those from la Borraca creek visited today, and small faulted blocks that appear in a small path south of la Barrosa Creek. This formation records the regional lower-middle Cambrian boundary, marked by the first appearance datum (FAD) of the trilobites *Acadoparadoxides mureroensis*. The formation has been intensely studied in the Murero and Jarque sections (Liñán *et al.*, 2008). In Purujosa, only few trilobites have been recovered including *Protolenus termierelloides* and *Alueva hastata* (Fig. 25B, D-E), brachiopods (*Trematobolus borobiensis*), algal filaments (Fig. 25C) and trace fossils.

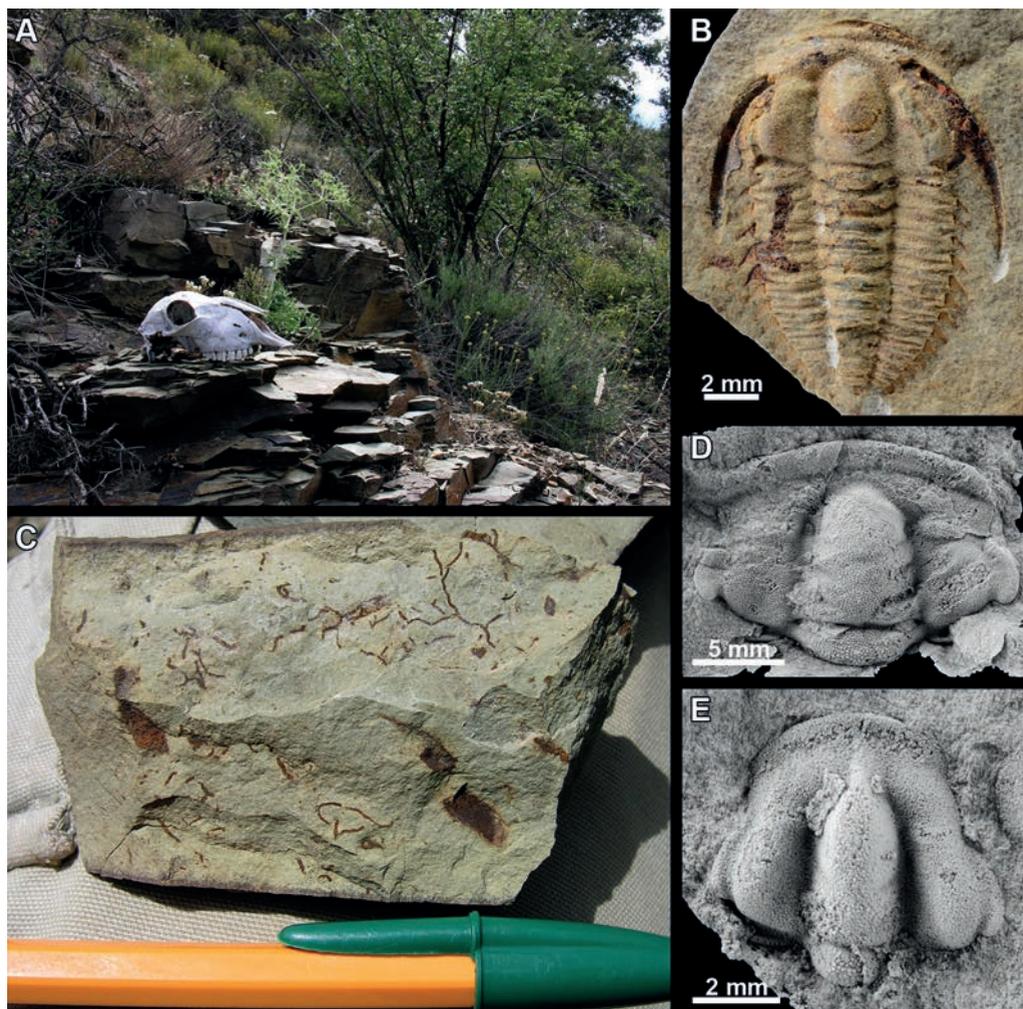


Figure 25. General aspects of the Valdemiedes Formation and fossil content. A. Laminated shales. B. Articulated specimen of *Protolenus termierelloides*. C. Fossil algae preserved as carbon films. D. Cranium of *Protolenus termierelloides*. E. Cranium of *Alueva hastata*. D and E are photographs from latex cast whitened with NH_4Cl sublimated.

STOP 7: Faunas from the Miaolingian Mansilla Formation

Location

Following the path from stop 2 and passing through the Parideras del Prado, the Mansilla Formation crops out along both sides of the path. Just before the path crosses La Borraca Creek, there is a well exposed outcrop to the left slope that encompasses part of the Pur 4 section (Fig. 22, 24).

Coordinates: 41°40'21.27"N, 1°47'16.78"W.

Geological map of Spain, 1:50.000, sheet of Tabuena (352).

Geological setting: Badules Unit (eastern Iberian Chain).

Lithostratigraphic unit: Mansilla Formation.

Age: Miaolingian-Wuliuan (regional Leonian).

Aims

Look at the diverse fauna from the Mansilla Formation consisting of trilobites, brachiopods, molluscs and echinoderms (including cinctan echinoderms and isolated plates belonging to dibrachicystid blastozoans).

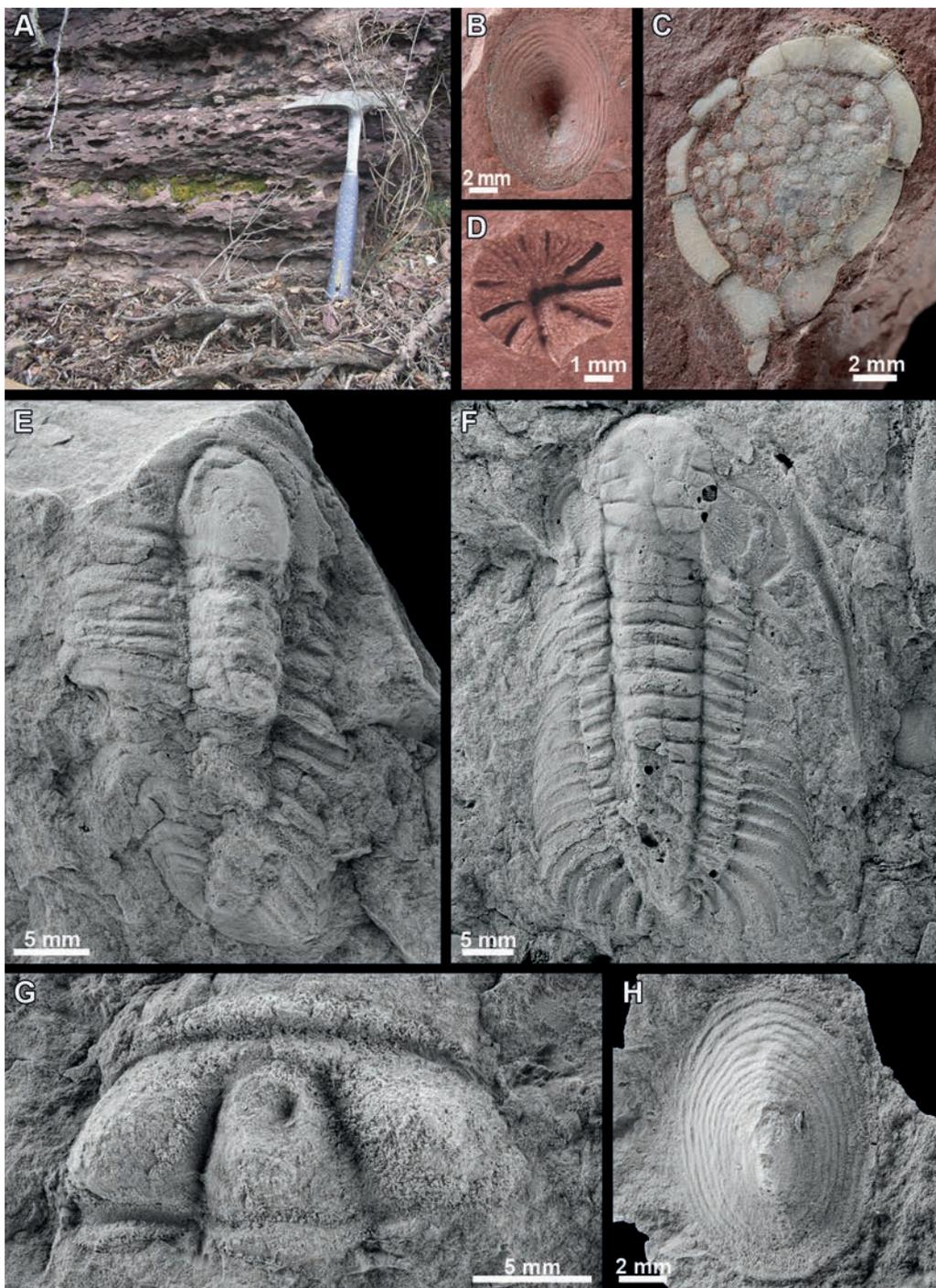
Description

The Mansilla Formation comprises here a 70 m-thick interval (Fig. 24) composed of red-purple shale/limestone couplets (the so-called 'griotte facies') passing up-section into shales with interbedded carbonate nodules (Fig. 26A). The upper part of the formation is more fossiliferous and dominated by shales. The formation shows a general transgressive trend from onshore to offshore deposits and, due to sharp changes in biozonal thickness, represents episodes of carbonate production on the top of palaeohighs surrounded by lows with mud-dominated sedimentation (Álvarez and Vennin, 1996a). The Valdemiedes and Mansilla formations record sharp lateral modifications in thickness and facies, and represent a stepwise breakdown of part of the Iberian platform (Cantrabro-Iberian Basin) with episodes of microbial and shelly carbonate production reflecting Milankovitch-like cyclicities (Álvarez *et al.*, 1993b, 1996a, b, 2010; Álvarez and Clausen, 2005).

Cinctan echinoderms are very abundant throughout the section but complete specimens have only been reported from the upper part of the formation (Fig. 26C, 27), where they are found alongside dibrachicystid isolated plates (Fig. 26D), trilobites such as *Badulesis* sp. A (= *Parasolenopleura ouangondiana*), *Eccaparadoxides rouvillei*, and *Parabailiella schmidti* (Fig. 26E-G), brachiopods and molluscs (Fig. 26B, H). Although the trilobites from this formation have been studied by several authors (eg. Gozalo and Liñán, 1996, Liñán and Gozalo 2011, Gozalo *et al.* 2005, Chirivella Martorell, 2008, Chirivella Martorell *et al.* 2003, 2009), in Purujosa only the echinoderms have been studied in detail.

In contrast to other formations in the area, echinoderms of the Mansilla Formation are preserved as calcite. Detailed studies of these specimens using cathodoluminescence revealed the original stereom microstructure in recrystallized calcite plates that was invisible under conventional transmitted light or SEM (Gorzelać and Zamora, 2013).

The species *Protocinctus mansillaensis* (Fig. 27A-B) has been named from these beds using CT-scans combined with traditional techniques (Rahman and Zamora, 2009). The inclusion of this taxon into a cladistic analysis revealed its basal position within the sucocystid clade (Smith and Zamora, 2009), which is not unexpected if we consider the taxon as the oldest cinctan from Gondwana. *P. mansillaensis*



has been studied using computational fluid dynamics analyses (Fig. 27C) in order to understand its mode of life and feeding strategy (Rahman *et al.*, 2015). Simulations of water flow passing through three-dimensional digital models of *Protocinctus* (Fig. 27C) in a range of possible life positions, adopting both passive tentacular feeding and active pharyngeal filter feeding demonstrated that an orientation with the mouth facing downstream of the current was optimal for drag and lift reduction. Moreover, they show that there was almost no flow to the mouth and associated marginal groove under simulations of passive feeding, whereas considerable flow towards the animal was observed for active feeding, which would have enhanced the transport of suspended particles to the mouth. This strongly suggested that cinctans were active pharyngeal filter feeders (Fig. 27D), like modern enteropneust hemichordates and urochordates, indicating that the ancestral deuterostome employed a similar feeding strategy.

Based on the trilobite content, those levels correspond with the regional *Eccaparadoxides asturianus* Zone, which is considered as late Leonian in age (Sdzuy *et al.*, 1999).

Figure 27. The oldest cinctan echinoderm *Protocinctus mansillaensis* from the Mansilla Formation. A. Holotype complete specimen. B. CT-scan in oblique view of the holotype. C. Recreation of water flows around the specimen, considering that currents were directed from posterior to anterior. D. Reconstruction of *P. mansillaensis*. Images after Rahman *et al.* 2015.

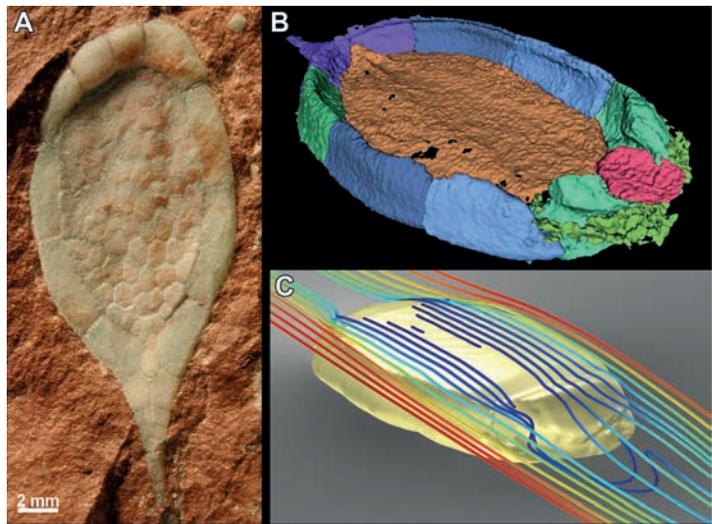


Figure 26. General aspect and fossils from the Mansilla Formation. A. General view of shales with intercalated carbonate nodules (griotte facies). B. External mold of *Marocella* sp. C. The cinctan *Asturicystis* sp. preserved in calcite. D. thecal plate of dibrachycystidae indet. E. Complete specimen of *Solenopleura* sp. F. Complete specimen of *Eccaparadoxides rouvillei*. G. Cranium of *Parabailiella schmidti*. H. Latex cast of *Marocella* sp. figured in B (previous page).



STOP 8: The Murero Formation and the diversification of benthic communities

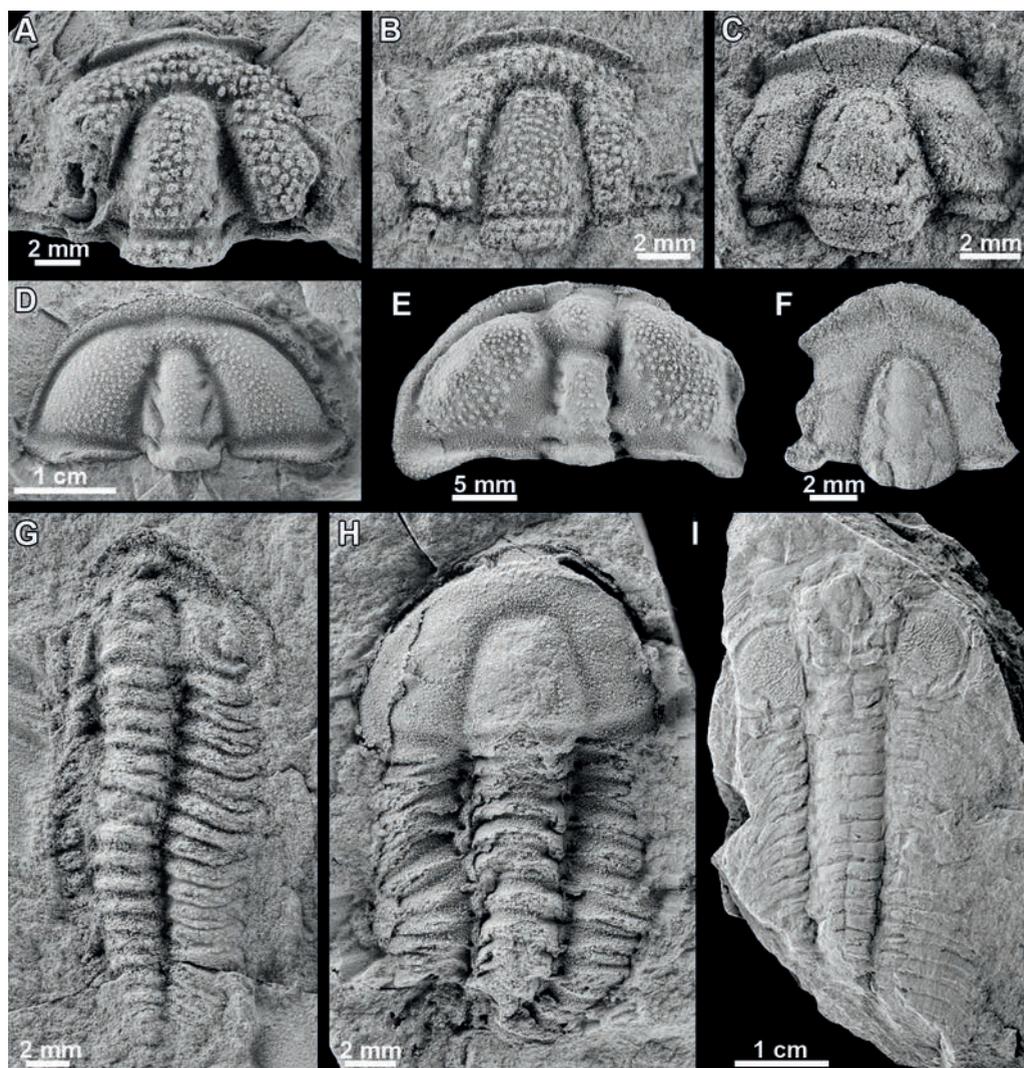
Location

Following the aforementioned path until it turns left 90°, and then abandoning the path to the south-east slope of Matarrañas hill arriving at a small ravine that comprises the top of the Mansilla Formation and most of the Murero Formation (Pur 6 section) (Figs. 22, 24).

Coordinates: 41°40' 11.70"N, 1°47'16.91"W

Geological map of Spain, 1:50.000, sheet of Tabuena (352).

Geological setting: Badules unit (eastern Iberian Chain).



Lithostratigraphic unit: Murero Formation.

Age: Miaolingian, Wuliuan-Drumian (regional Caesarugustan).

Aims

Look at classic trilobite and echinoderm assemblages with high diversity from the Murero Formation.

Description

The Murero Formation is the most fossiliferous interval in the area and reflects a peak in the diversity of trilobites throughout the Iberian margin of Gondwana (Álvaro *et al.*, 1999, 2003, 2007, 2013b). It shows about 80 m of green to yellowish shales with locally interbedded nodules deposited in offshore-dominant environments. The palaeogeographic position of Purujosa at the most distal part of the Iberian Platform (part of the Cantabro-Iberian Basin) favored preservation of multiple obduction events in which articulated echinoderms and complete trilobites are common. Several small quarries in the base of the formation have yielded abundant trilobites and echinoderms, including agnostids, such as *Peronopsis fallax* (= *P. acadica*), *P. segmentata*, *Condylopyge rex*, *Perenopsella westergardi* and *Diplagnostus planicauda*; trilobites (*Badulesia tenera*, *B. granieri*, *Pardailhania hispida*, *P. multispinosa*, *Eccaparadoxides rouvillei*, *E. sequeirosi*, *E. pradoanus*, *Hydrocephalus donayeri*, *Parabailiella languedocensis*, *Conocoryphe heberti*, *Ctenocephalus antiquus* and *Agraulos longicephalus*); echinoderms (*Gyrocyrtis platessa*, *G. testudiformis*, *Graciacyrtis ambigua*, *Ctenoimbricata spinosa*, *Courtessolea* sp., *Vizcainoia moncaiensis*, *Ceratocystis* sp., brachiopods and sponges (Figs. 28-31).

The *Ctenoimbricata* quarry (Fig. 30A) is remarkable because of the importance of this taxon for the evolution of echinoderms. The quarry has yielded two specimens of *Ctenoimbricata spinosa* (Fig. 30), one ctenocystoid specimen *Courtessolea* (Fig. 31E-F), several

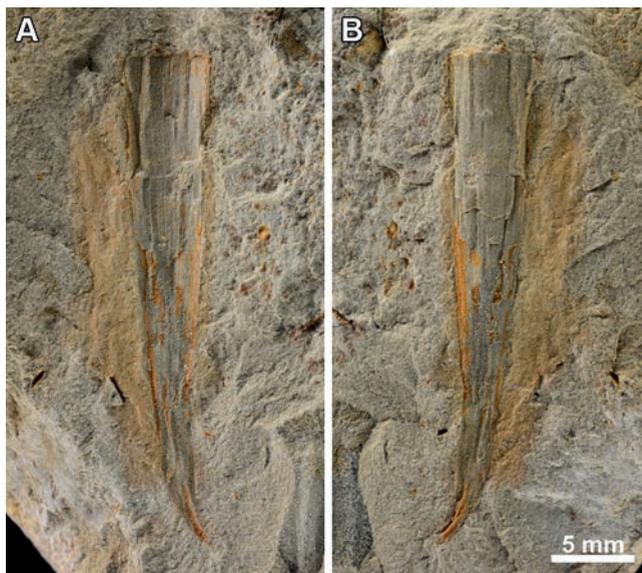


Figure 29. Complete specimen of the sponge *Leptomitius conicus*, part (A) and counterpart (B) collected from the base of the Murero Formation in the Purujosa 6 section.

Figure 28. Trilobites from the Murero Formation. A. Cranium of *Manublesia ribeiroi*. B. Cranium of *Manublesia thoralii*. C. Cranium of *Badulesia tenera*. D. Cranium of *Conocoryphe heberti*. E. Cranium of *Ctenocephalus antiquus*. F. Cranium of *Schopfaspis? graciai*. G. Articulated specimen of *Badulesia granieri*. H. Articulated specimen of *Agraulos longicephalus*. I. Articulated specimen of *Eccaparadoxides rouvillei*.

Photographs of A, D, E, G, H and I are internal molds; B, C and F are from latex casts, all whitened with NH_4Cl sublimated (previous page).

specimens of *Ceratocystis* sp., the eocrinoid *Gogia* sp., the cinctan *Graciacystis ambigua* and isolated plates of dibrachycystids (Zamora, 2010, 2011; Zamora *et al.*, 2012, 2013).

Ctenoimbricata (Fig. 30) is a very important fossil and requires further attention. It is a small (20 mm), disc-like animal with a clearly defined anterior–posterior axis and with bilaterally symmetric skeletal ele-

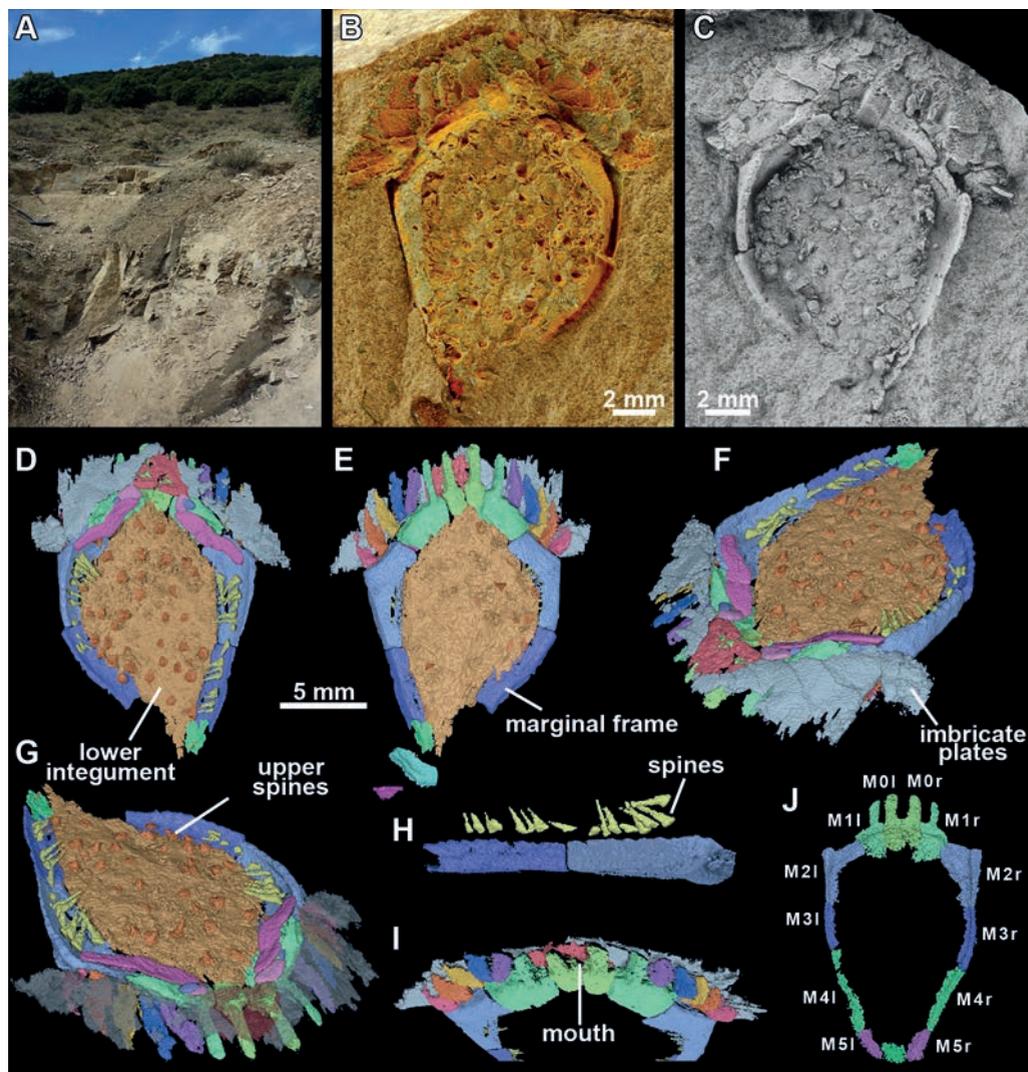


Figure 30. The bilateral echinoderm *Ctenoimbricata spinosa*. A. General view of the quarry where *Ctenoimbricata* was collected in levels from the base of the Murero Formation at Purujosa 6 section. B, C. *Ctenoimbricata spinosa* preserved as natural mould (B) and latex cast from the same specimen (C). D–J. CT scan images of *Ctenoimbricata spinosa*. D, E. Dorsal and ventral views. F. Oblique left view. G. Oblique right view with the dorsal ctenidium partially transparent to show the ventral ctenoidal plates. H. Lateral view of two marginal plates showing the articulation of the spines. I. Frontal view. J. Marginal frame plates after correction of plate orientations. Abbreviations: M, marginal plate; l, left; r, right.

ments arranged along that axis. A uniserial marginal ring of stout plates frames the body, comprising four elements at the anterior forming part of the ctenidium, four on either side plus a single posterior element (plate Mp). Dorsal and ventral plated membranes cover the centre of the disc. At the anterior part, there is a wide opening framed by marginal plates and covered dorsally by a sheet of imbricate plates. This dorsal roof is formed by several superimposed series of thin, flat plates that imbricate posteriorly. A row of very small spinose plates forms the outermost dorsal row. The dorsal ctenidium formed a single unit with limited flexibility. Ventrally, the opening is lined anteriorly by 14 spinose elements. The four median ones are anterior extensions of marginal frame plates M0 and M1. The remaining 10 are free elements that articulated with the outer edge of marginal plates. Distally, these plates taper, becoming knife-like in outline, and overlap from posterior to anterior. The periproct is not observed but certainly does not pass through the marginal ring, as this structure is unbroken. It must therefore be situated in the dorsal membrane, and the only part of that structure missing from our specimen is the very posterior. By comparison with the closely related genus *Courtessolea*, the periproct should have opened in the posterior part of the dorsal membrane, close to plate Mp. *Ctenoimbricata* is an important taxon for deciphering echinoderm basal relationships, and was interpreted as a basal echinoderm based on its bilateral morphology and absence of radial symmetry (Zamora *et al.*, 2012).

STOP 9: Red beds from the upper part of the Miaolingian Murero Formation – a ‘hot spot’ of enrolled trilobites and echinoderms

Location

Ascend the previous aforementioned ravine until we reach the main path, and then turn left until the path crosses the red beds forming the top of the Murero Formation. Then abandon the main path to the south to reach a big quarry in which red beds have been excavated (Fig. 22).

Coordinates: 41°40'7.37"N, 1°47'23.79"W

Geological map of Spain, 1:50.000, sheet Tabuenca (352).

Geological setting: Badules unit (eastern Iberian Chain).

Lithostratigraphic unit: Murero Formation.

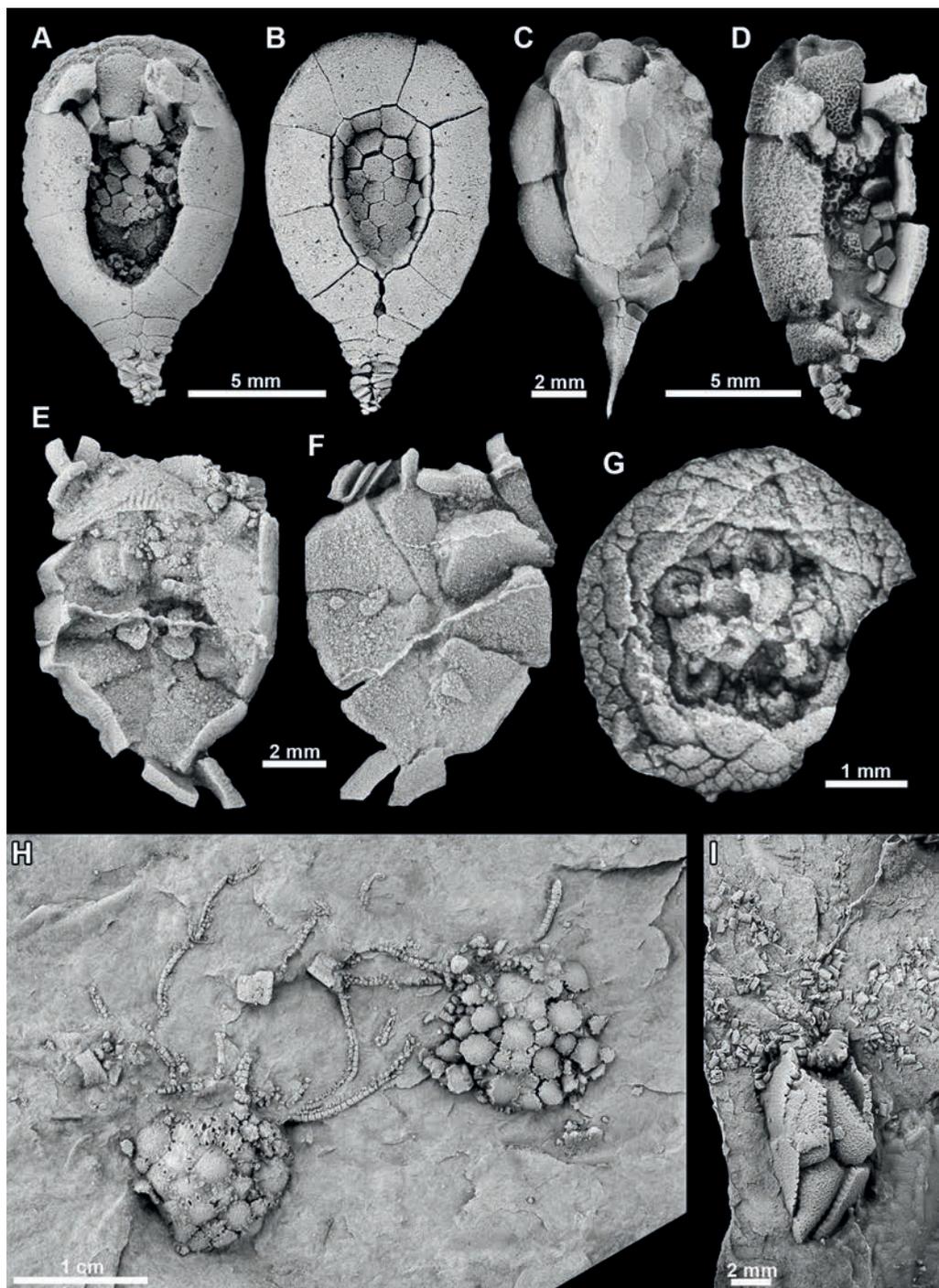
Age: Miaoliangian, Drumian (regional Languedocian).

Aims

Look at one of the most important Cambrian assemblages from Spain consisting on highly diversified echinoderms and abundant trilobites. Discuss the peak in Cambrian echinoderm diversity from Gondwana based on a single outcrop with a high diversity of echinoderms comprising eight different taxa.

Description

The red beds that characterize the upper part of the Murero Formation in the study area have been excavated through more than eight years for detailed taphonomic and taxonomic studies. They include a thin layer (< 1m thick) of weakly bioturbated shale (ichnofabric index 1–2 of Droser and Bottjer, 1986) that stands out from adjacent beds by an abrupt change in colour: beds immediately overlying and underlying the layer are green-grey. The associated fauna includes echinoderms, such as the edrioasteroid *Protoro-*



phus hispanicus (Fig. 31G), the cinctan *Gyrocystis platessa*, the stylophorans *Ceratocystis* sp. (Fig. 32B), plus two different undescribed cothurnocystids, and the blastozoans *Gogia gondi*, *Lichenoides* sp. (Fig. 31I) and *Dibrachicystis purujoensis* (Fig. 32A); polymerid trilobites, including *Eccaparadoxides pradoanus* Fig. 32E, H-I, *Conocoryphe heberti*, *Manublesia thoralis* (Fig. 32J), *Manublesia riberi* (= *Manublesia marginata*), *M. verdiagana*, *Schopfaspis? graciai* (Fig. 32C); agnostoids such as *Condylopyge* sp., *Peronopsis acadica*, *P. ferox*, *Pleuroterium* sp. and *Megagnostus* sp. (Fig. 32D); and both orthid (Fig. 32F) and lingulid (Fig. 32G) brachiopods (Zamora, 2009, 2010; Esteve, 2011; Esteve *et al.*, 2011; Mergl and Zamora, 2012). The FAD of the trilobite *Manublesia thoralis* marks the base of the regional Languedocian Stage *sensu* Álvaro and Vizcaino (1998), originally defined in the southern Montagne Noire (France).

These beds are unusual in two aspects: (i) the high diversity of echinoderms by comparison with coeval occurrences; and (ii) the large number of different trilobite taxa preserved in enrolled position.

The assemblage of enrolled trilobites was described by Esteve *et al.* (2011) and occurs throughout the bed. The trilobite fossils recovered at Purujosa are likewise notably diverse, but the bed is even more important as the world's oldest assemblage containing abundant enrolled trilobites (Esteve *et al.*, 2011). Until the discovery of the Purujosa assemblage, enrolment was considered rare among Cambrian trilobites, a notion supported by the fact that it was structurally impossible for some early forms (Whittington, 1990), even some enrolment styles (e.g. sphaeroidal or discoidal) were not achievable for Cambrian trilobites. Purujosa shows that a wide variety of trilobite body plans common in the Cambrian could enroll, prompting a fundamental reevaluation of the evolution of trilobite enrolment (Esteve *et al.*, 2011). The abundance of these enrolled trilobites at Purujosa allowed Esteve *et al.* (2011) to assess modes of enrolment among these early trilobites. It is noteworthy that each of the classical enrolment types (i.e. spiral enrolment and sphaeroidal and subtypes; see Esteve, 2013 for more details) are represented in the Purujosa assemblage. Furthermore, two or more of these enrolment types are represented within the genera *Manublesia* and *Conocoryphe*. The importance of this result is twofold: (i) it demonstrates that several modes of enrolment were available to contemporaneous individuals belonging to the same Cambrian genera; and (ii) it is noticeable that closely related individuals, sometimes even belonging to the same species (e.g., *Manublesia thoralis*), may differ in the manner of enrolment. On the other hand, this assemblage shows the importance of enrolment for the evolution of the post cephalic segmentation in trilobites since enrolment plays an important role of selective pressure favouring the caudalization process, which is the allocation of an increased proportion of the post cephalic segments to the holaspid pygidium (Esteve *et al.*, 2013).

Another important aspect of trilobite palaeobiology is that some specimens show repaired injuries (Fig. 33) in the form of shortened spines (Zamora *et al.*, 2011; Pates *et al.*, 2017). Contrasting to injuries on other Cambrian trilobites spines were not significantly more likely to be injured on the left or right sides. Spines on the rear three thoracic segments were more likely to be injured than other locations, and injuries on *Eccaparadoxides pradoanus* were interpreted as likely result from predatory attacks, rather than from accidents and/or problematic moulting (Pates *et al.*, 2017). The frequency of injuries at Purujosa are higher than the contemporaneous fauna of *Eccaparadoxides pradoanus* at the nearby Mesones de Isuela

Figure 31. Echinoderm faunas from the Murero Formation at Purujosa. A, B. Dorsal and ventral view of the cinctan *Gyrocystis platessa*. C. Dorsal view of the cinctan *Gyrocystis testudiformis*. D. Dorsal view of the cinctan *Gyrocystis erecta*. E, F. Dorsal and ventral view of the ctenocystoid *Courtessolea* sp. G. Oral view of the isorophid edrioaasteroid *Protorophus hispanicus*. H. Two specimens of the eocrinoid *Gogia parsleyi*. I. The eocrinoid *Lichenoides* sp. All photographs are from latex cast whitened with NH₄Cl sublimated.



locality, however broken trilobite sclerites are common at both localities. These broken sclerites originated from successful predatory and/or scavenging events, and abiotic damage (e.g. during transport), although in some cases the cause cannot be confidently determined (Pates *et al.*, 2017). Taken together, both frequency of enrolled trilobites and repaired injuries from paradoxiid trilobites provides strong evidence of predator-prey interactions in the arm-race that was ongoing by the Cambrian.

Echinoderms are here more diverse than in any other Cambrian deposits with the exception of a recently discovered level in Morocco (Smith *et al.*, 2013) that still is in need of further study. From the total sample (150 complete specimens), only one specimen is a 3 mm-long isorophid edrioasteroid that corresponds to the oldest record of this group (Zamora and Smith, 2010). There are also two specimens of cothurnocystids belonging to two different species that represent the oldest record of such a clade in Gondwana (Zamora, 2009, 2010, 2011). Other echinoderms, such as cinctans, armoured stylophorans and blastozoans are more abundant. This informs us about how rare some groups were in the Cambrian and the type of methodology needed to collect those groups. The presence of eight different taxa in the same bed indicates that niche partitioning was already established by mid Cambrian times. In fact, these species are very different in their mode of feeding and attachment as revealed by their different morphologies.

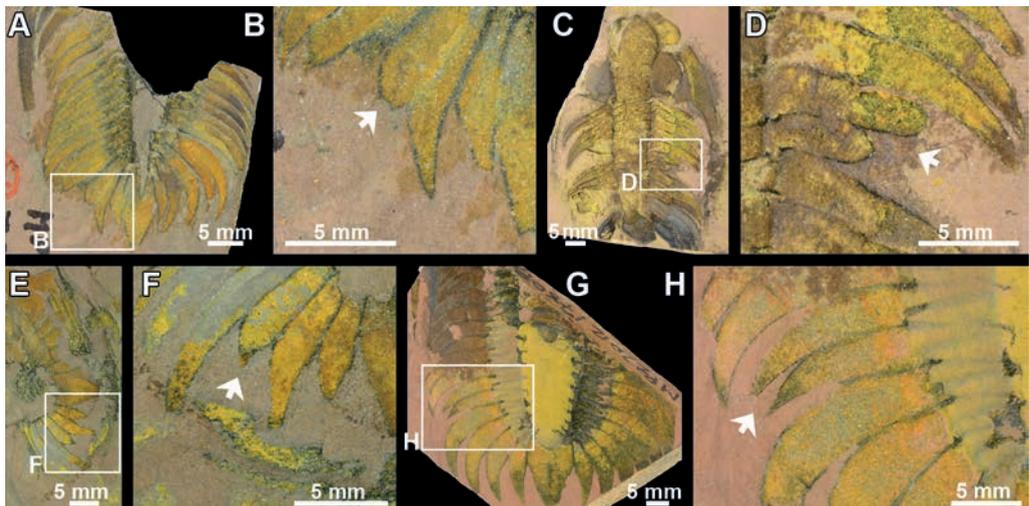


Figure 33. Specimens of *Eccaparadoxides pradoanus* collected from the red beds of the Murero Formation showing shortened pleurae.

Figure 32. Fossils collected from the red beds of the Murero Formation. A. The blastozoan *Dibrachycystis purujoensis*. B. The stylophoran *Ceratocystis* sp. C. The trilobite *Schofaspis? graciae*. D. The agnostoid *Megagnostus* sp. E. The trilobite *Eccaparadoxides pradoanus*. F. The rhynchonelliformean brachiopod *Brahimorthis alvaroi*. G. Lingulid brachiopod *Micromitra* sp. H, I. Enrolled specimens of the trilobite *Eccaparadoxides pradoanus*. J. Enrolled specimen of the trilobite *Solenopleuropsis thoralis* (previous page).

STOP 10: Siliceous concretions from the Valtorres Formation**Location**

Following the path for several kilometres up to Collado de Piedras that passes through the Peña del Águila and Cocota del Rincón, both considered the top of the Encomienda Formation, and entering to the municipality of Pomer. The path goes down the slope from Collado, and approximately 300 m to the left the shales of the Valtorres formation crops, which contains siliceous concretions (Fig. 21).

Coordinates: 41°38' 56.94"N, 1°48'39.33"W
 Geological map of Spain, 1:50.000, sheet of Illueca (381).
 Geological setting: Badules unit (eastern Iberian Chain).
 Lithostratigraphic unit: Valtorres Formation.
 Age: Miaoliangian, Guzhangian (regional Languedocian).

Aims

Look at a rich assemblage of trilobites, bradoriids, molluscs, brachiopods and trace fossils preserved in siliceous concretions from the Valtorres Formation (Figs. 34-35). Discuss the extension of the regional Languedocian Stage and correlation with other areas.

Description

The Valtorres Formation in Purujosa is incomplete and only its lower part is exposed. It mainly consists of shales with fine sandstones interbeds, which contain siliceous concretions concentrated in an interval about c. 10 m thick located 6 m above the Encomienda/Valtorres contact. Taxonomic determination of trilobites from these fossiliferous concretions occurs in Álvaro *et al.* (2013a). Esteve and Zamora (2014) and Esteve *et al.* (2017) provided examples of some enrolled trilobites within these fossiliferous concretions. The sandy intervals provide a rich ichnofossil assemblage mostly composed of *Treptichnus* isp. (Fig. 35H), *Petalichnus* isp. (Fig. 35J) and indeterminate arthropod trackways (Fig. 35I). The concretions consist of a mixture of terrigenous material (quartz and phyllosilicates such as illite/muscovite and chlorite) and biogenic components (calcite- and apatite-walled skeletons). Crystalline micro- and megaquartz (< 20 µm and > 20 µm, respectively) are the most abundant siliceous types. They occur both as replacement and as pore-lining and pore-filling cements in interparticle and moldic porosities. Crystals are euhedral and equant, 10 to 150 µm in size, and display a mosaic texture similar to drusy mosaics. Siliceous cement shows an irregular poikilotopic texture due to pore-occluding cements. Where present, megaquartz represents the last pore-filling siliceous phase. The original high porosity was due to the morphology and arrangement of skeletal material (Álvaro *et al.*, 2013a).

Dolomite occurs as finely crystalline to microsparite, subhedral to anhedral crystals. The presence of clear dolomite rhombs, 20–30 µm in size, within the iron-oxide stained chert suggests that some dolomitization occurred before silicification. Pyrite is found as dispersed euhedral crystals, mainly pyritohedra and cubes, ranging from 15 to 50 µm in size, and represents less than 5 % in volume of the components. Goethite and hematite also appear occasionally (particularly in the incompletely silicified concretions) as botryoidal networks or crusts, up to 4 mm thick and subsequently lined with siliceous (Álvaro *et al.*, 2013a).

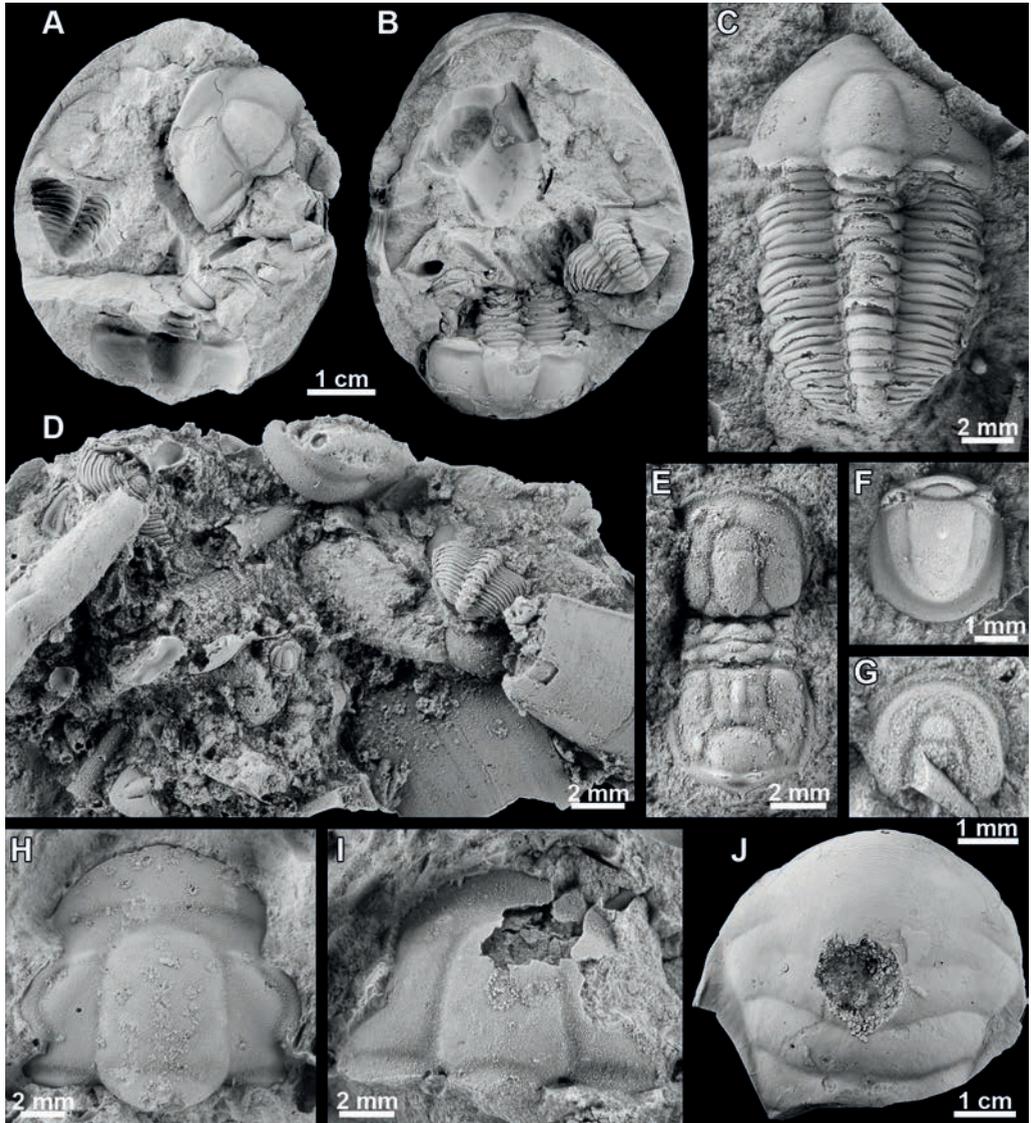
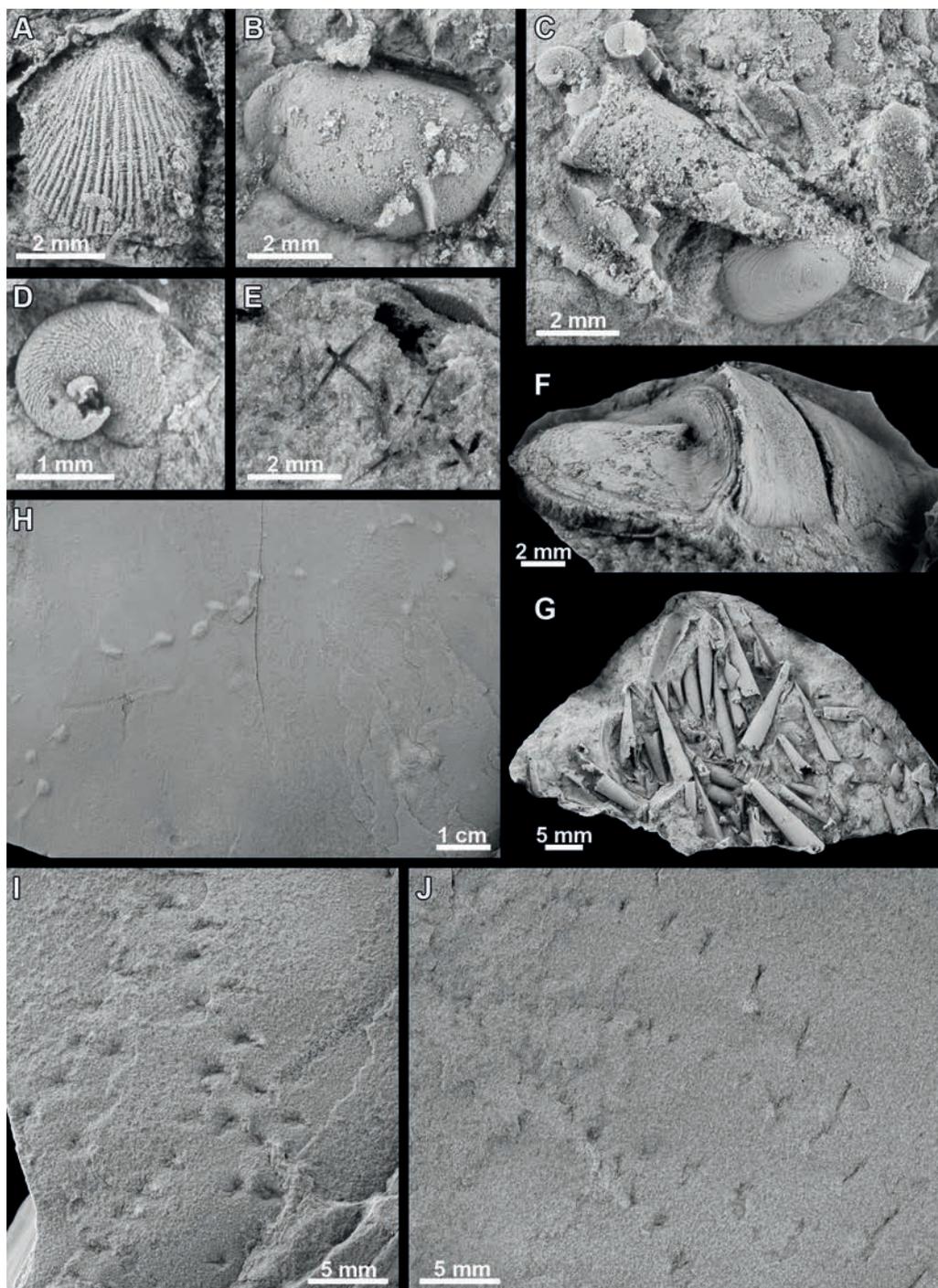


Figure 34. Trilobites from the Valtorres Formation. A, B. Complete concretion showing several specimens of *Bailliaspis? glabrata*. C. Complete specimen of *Bailliaspis? glabrata*. D. General view of a concretion with hyolithids and enrolled specimens of *Bailliaspis? glabrata* and *Peronopsis cf. insignis*. E. Complete specimen of the agnostoid *Oidagnostus trispinifer*. F. Complete enrolled specimen of *Peronopsis cf. insignis*. G. Cranidium of *Peronopsis cf. insignis*. H. Cranidium of *Proampyx difformis*. I. Cranidium *Holasaphus cf. centropyge*. J. Partial cranidium of *Paradoxidid* indet. Photographs C-F are from latex cast whitened with NH_4Cl sublimated.



Shelly accumulations are concentrated within the concretions (in the centre, at the margin or wholly dispersed). The shells are dominantly disarticulated and fragmented although a few complete and enrolled trilobites have also been encountered. The shells and skeletons in the concretions do not show any deformation, contrary to those sparsely preserved in the host rock. Hexactinellid sponge spicules (Fig. 35E), originally siliceous, are ubiquitous and have been completely replaced by ferroan dolomite and goethite. The spicules, mainly monaxons and triaxons bearing a central channel, and 0.1 to 4 mm long, are disarticulated. It is assumed that the siliceous building up the tiny authigenic quartz of the concretions was derived from dissolution of these spicules. The concretions contain a diverse shelly fauna, composed of trilobites, such as *Peronopsis* cf. *insignis* (Fig. 34D, F-G), *Oidalagnostus trispinifer* (Fig. 34E), *Proampyx difformis* (Fig. 34H), *Bailiaspis?* *glabrata* (Fig. 34A, C-D), *Holasaphus* cf. *centropyge* (Fig. 34J), and a paradoxiid gen. et sp. indet. (Fig. 34J), calcitic and linguliformean brachiopods (Fig. 35A, C), helcionellids (Fig. 35C-D), hyoliths (Fig. 35F-G), hexactinellid sponge spicules (Fig. 35E), and subsidiary bradoriids (Fig. 35B) (Álvaro *et al.*, 2013a). The fossil record allows the recognition of a strong biogeographical link with Baltica, and the correlation of the global Guzhangian Stage and the *Solenopleura?* *brachymetopa* Zone of Scandinavia with part of the Mediterranean upper Languedocian Substage (Álvaro *et al.*, 2013a).

CAMBRIAN OF MURERO

Fossils from the locality of Murero have been known since 1862 when De Verneuil discovered Barande's "primordial fauna" based on trilobites (Anonymous, 1862). The best sections in the area crop on both sides of Rambla de Valdemiedes (Fig. 36A, C). Major monographs focused on trilobites have been published by Sdzuy (1961) and Liñán and Gozalo (1986). Subsequently, several PhD theses were focused on the trilobite content (Álvaro, 1994; Dies Álvarez, 2004; Chirivella, 2008; Esteve, 2011), ichnofossils (Gámez Vintaned, 2007) and echinoderms (Zamora, 2009). The sections are important in terms of international correlation as one of the main important locations where the traditional lower-middle Cambrian boundary in the Mediterranean region can be recognized (Liñán *et al.*, 2008).

STOP 11: Levels with exceptional preservation from the Valdemiedes and Murero Formations

Location

Rambla de Valdemiedes; road connecting Puerto de Villafeliche with Murero (Fig. 36C).
 Coordinates: 41°10'2.57"N, 1°28'35.01"W
 Geological map of Spain, 1:50.000, sheet of Paniza (438).
 Geological setting: Badules unit (western Iberian Chain).
 Lithostratigraphic unit: Valdemiedes and Murero formations.
 Age: Cambrian Series 2-Miaolingian, Stage 4-Drumian (Bilbilian-to-Languedocian).

Figure 35. Invertebrate fauna and trace fossils from the Valtorres Formation. A. Rhynchonelliformean brachiopod indet. B. Bradoriid indet. C. Hyolithid shell with a linguliformean brachiopod attached and helcionellid. D. Helcionellid indet. E. Hexactinellid spicules. F, G. Hyolithid shells. H. *Treptichnus* isp. I. Indeterminate arthropod trackway. J. *Petalichnus* isp. (previous page). Photographs A-D, F, G are from latex cast whitened with NH₄Cl sublimated.

Aims

General view of the Rambla de Valdemiedes and formations from the Cambrian Mesones Group. Look at levels of exceptional preservation from the Valdemiedes and Murero Formation containing slightly sclerotized arthropods and sponges.

Description

Levels with slightly sclerotized fossils from Murero are known since 1986, when Conway Morris and Robison (1986) described the palaeoscolecid *Palaeoscolex* cf. *P. ratcliffei* from the Murero stratotype. The history behind this first specimen is interesting because it was collected by Gutiérrez-Marco in the Rambla de Valdenegro (a perpendicular creek that connects with Rambla de Valdemiedes) when looking for trilobites, and was sent to Conway Morris for study. Several years afterwards, Gámez (1995) published a second and better preserved specimen of the same taxon and Ferrer *et al.* (1995) described a new alga (*Aragonia sdzuy*) that likely represents a pseudo-fossil. In a meeting of the Spanish Palaeontological Society, Liñán *et al.* (1996) and García-Bellido and Liñán (1996) provided further evidence about the presence of Burgess-Shale type fossils in Murero, including algae and sponges. Main results from the MsC Thesis of García-Bellido where published in a paper in 1999, including a complete taphonomic study from a short interval of the Murero Formation in Rambla de Valdemiedes. Since then, several other papers have reported description of sponges from the Murero Formation, including *Leptomitus* cf. *L. lineatus* and *Leptomitus conicus* (García Bellido, 2003; García Bellido *et al.*, 2007). Soft bodied fossils have been reported also from the slightly older Valdemiedes Formation thanks to relatively large excavations that were carried out by Liñán in the 90s. These excavations provided a rich assemblage of shelly fauna and poorly mineralized taxa that were presented to the scientific community in a meeting focused on exceptional preservation (Liñán, 2003). The Valdemiedes Formation includes the sponge *Crumillospongia mureroensis* described by García Bellido *et al.*, 2011 (Fig. 37B) and the radiodont *Caryosyntrips* cf. *C. camurus* (Fig. 37F) recently



Figure 36. A. General view of Rambla de Valdemiedes. B. Coat of arms of Murero village showing a paradoxiid trilobites from the area. C. Geological map of the surroundings of Murero; modified from Gozalo and Liñán (1986).

re-described by Pates and Daley (2017). The latter was originally described as a partial body of a lobopodian (Gámez-Vintaned *et al.*, 2011); however comparisons with well-preserved material from the Burgess Shale and Cambrian deposits in Utah allowed assignment of this specimen to *Caryosyntrips* (Pates and Daley, 2017, though see subsequent discussion in Gámez-Vintaned and Zhuravlev, 2018 and Pates *et al.*, 2018). *Caryosyntrips* is unusual among the radiodonts as its frontal appendages do not have well delin-

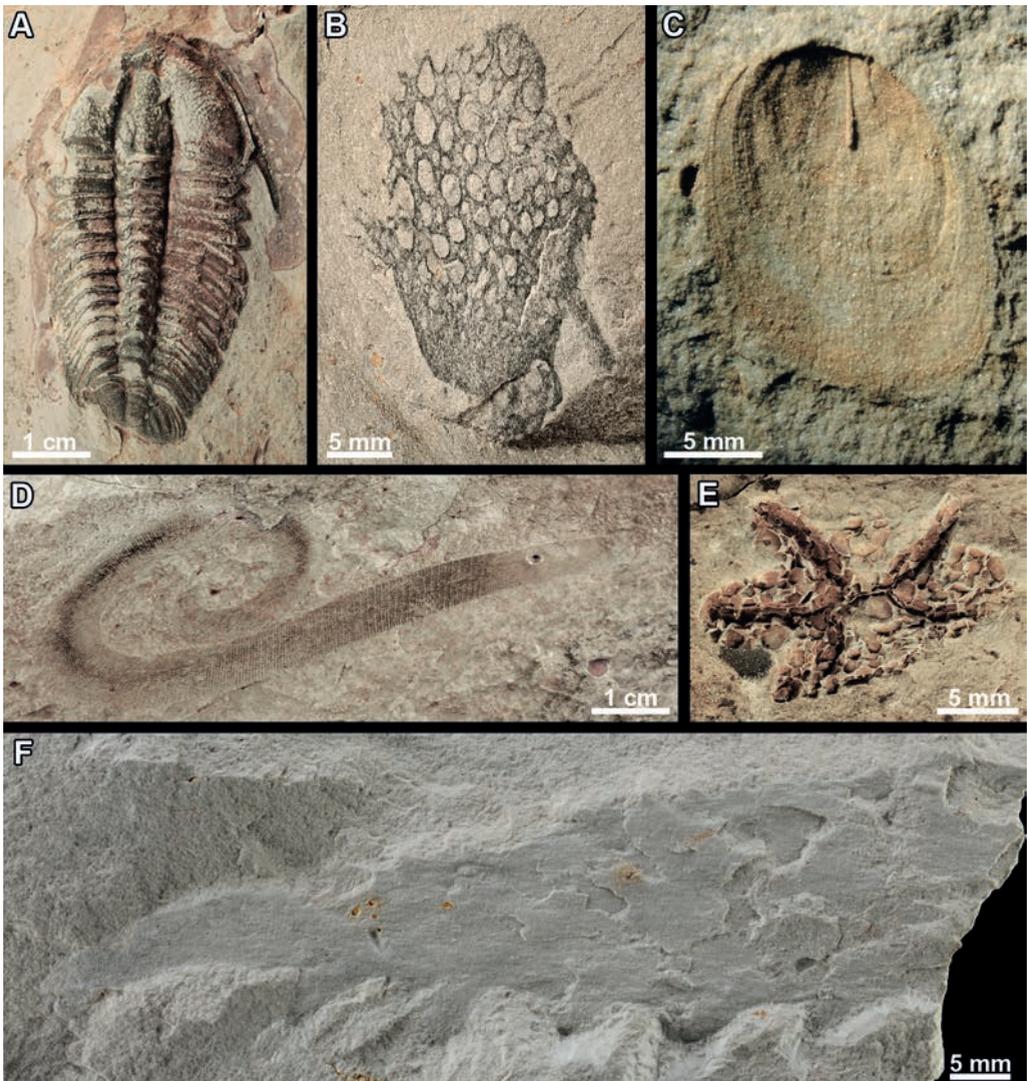


Figure 37. A. Fossils from the Valdemiedes (B, C, F) and Murero (A, D, E) Formations of Murero. A. Complete specimen of *Conocoryphe heberti*. B. The sponge *Crumillospongia mureoensis*. C. The brachiopod *Trematobollus simplex*. D. The palaeocolecid *Wronascolex?* sp. E. Complete edrioasteroid *Aragocystites bellus*. F. The radiodont *Caryosyntrips* cf. *C. camurus*. Images reproduced from Liñán *et al.* (2008) and Zamora *et al.* (2016).

eated arthrodial membranes, have a subtriangular outline when flattened, and possess short triangular spines along the inner margin. The Murero specimen is the largest *Caryosyntrips* known, and the oldest representative of the genus.

Liñán *et al.* (2009) suggested that the soft bodied preservation in Murero spans part of the classic "lower Cambrian" and almost the whole Miaolingian, but levels with slightly sclerotized fossils show a really low diversity and are concentrated in certain parts of the section. During this field excursion we will have the opportunity to visit some of those aforementioned levels: one in the Valdemiedes Formation (RV1/3-6); and the other in the Murero Formation (RV1/17.7). The former provided the sponge *Crumillospongia mure-roensis* (Fig. 37B) and the radiodont *Caryosyntrips* cf. *C. camurus* (Fig. 37F), associated with trilobites, echinoderms and brachiopods (Fig. 37C). The later provided mostly palaeoscolecsids (Fig. 37D), similar to those described by previous authors (see examples in García-Bellido *et al.*, 2013), trilobites (Fig. 37A) and echinoderms (Fig. 37E). Although these levels have been considered as Burgess-Shale type deposits by some previous authors (e.g., Liñán, 2003), fossils from Murero correspond to slightly sclerotized organisms only and entirely non-cuticularized animals are absent, which is a great difference between Murero and other important Cambrian deposits, such as the Burgess Shale and Chenjigiang biota (for a discussion, see Saleh *et al.*, 2020).

DAY 3: December 17th 2019

PRIDOLI TO EARLY DEVONIAN MARINE AND TERRESTRIAL COMMUNITIES AND STRATA FROM THE EASTERN IBERIAN CHAIN

José Ignacio Valenzuela-Ríos, Peter Carls, Claudia Dojen, Carlos Martínez-Pérez, Humberto G. Ferrón, Héctor Botella, Borja Cascales-Miñana and Jau-Chyn Liao

INTRODUCTION

During the early 1960's, Carls (1962, 1965) laid out the basic stratigraphical descriptions and subdivisions of the Silurian and Lower Devonian strata in the Iberian Chains. Subsequently Carls and Gandl (1969) and Carls *et al.* (1972) expanded the stratigraphic succession to the Eifelian (Middle Devonian) but descriptions were first provided in Carls (1988), a millstone paper for the Devonian of Celtiberia. Previously, Carls and Lages (1983) provided the stratigraphic frame for the Givetian, Frasnian and Famennian and

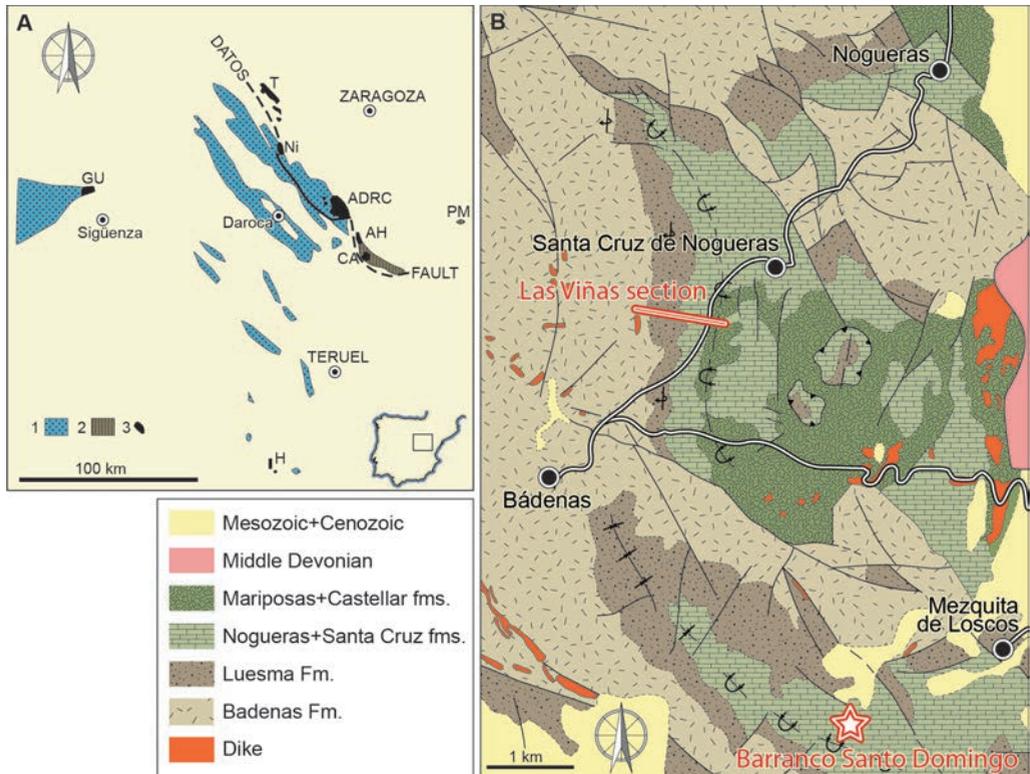


Figure 38. Simplified geological map of Celtiberia and location of the sections. A. Devonian and Carboniferous outcrops. GU. Guadarrama outcrops; H. Henarejos; T. Tabuenca; Ni. Nigüella; ADRC. Axial Depression of the Río Cámaras; PM. Puig Moreno; AH. Anadón-Huesa and CA. Cabezos Altos Devonian outcrops in the Montalbán Anticline; 1. Basement (Palaeozoic and Precambrian) of Celtiberia; 2. Carboniferous of the Montalbán Anticline plus Puig Moreno; 3. Devonian outcrops of Celtiberia. Based on Carls and Valenzuela-Ríos (2002a). B. Detailed geological map of the area to be visited with location of the Las Viñas Section and South Barranco de Santo Domingo outcrops.

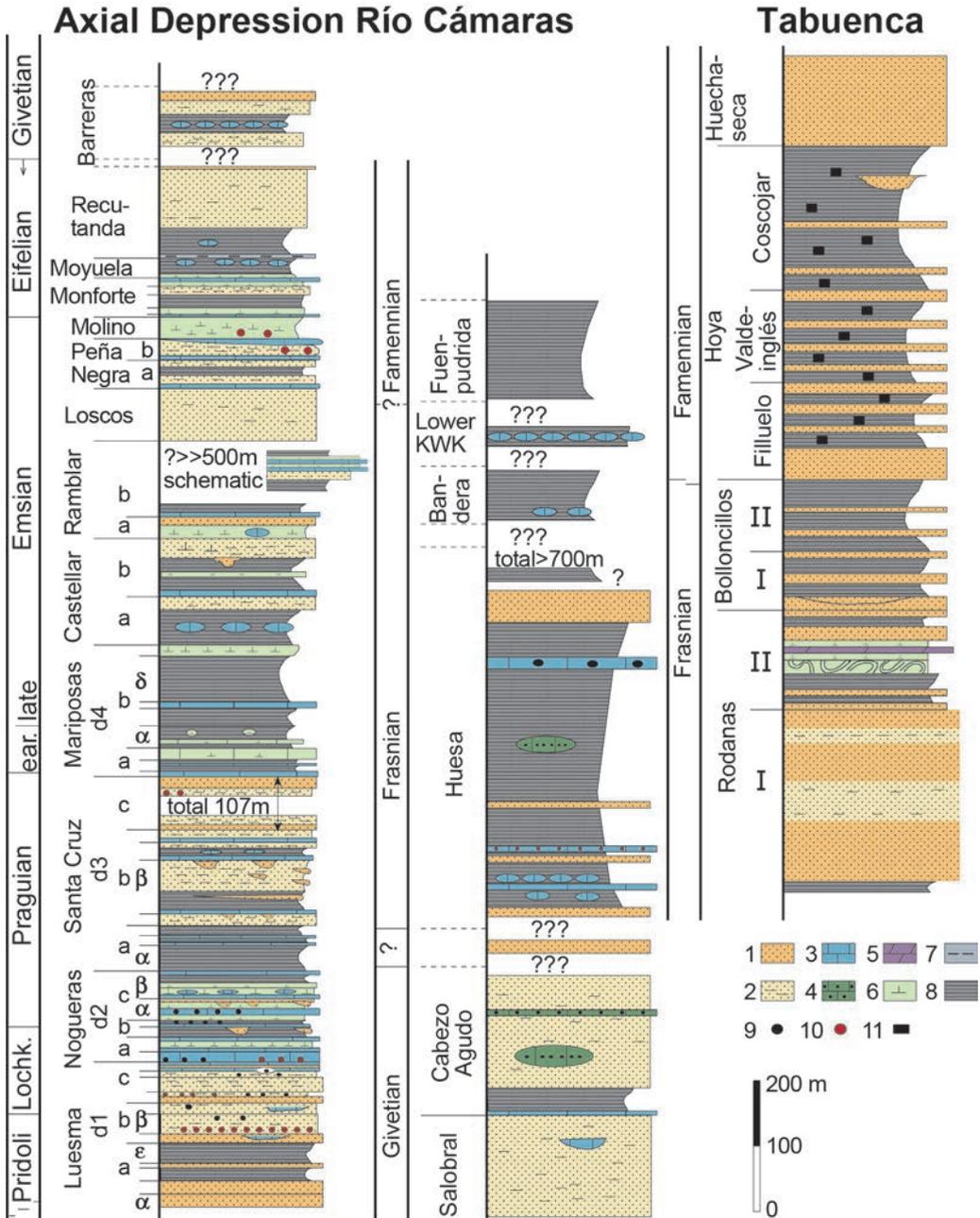


Figure 39. Devonian synthetic column of the Iberian Chains in two areas, ADRC and Tabuena, the latter only exposes Upper Devonian rocks. 1. Sandstone/ortoquartzite; 2. Sandstone-shale alternance; 3. Limestone; 4. Arenaceous limestone; 5. Dolostone; 6. Marl; 7. Silt; 8. Shale; 9. Phosphate nodules; 10. Iron nodules; 11. Silty nodules. Based on Carls and Valenzuela-Ríos (2002a).

Carls (1983), in a general paper devoted to the Palaeozoic of the Western-Leonese Zone, arranged all the Devonian stratigraphic formations that were previously disseminated in several papers. The pivotal work of Carls (1988) demonstrates the global relevance of the Devonian of Celtiberia in many aspects. He updated previous scattered and partial stratigraphic and faunal descriptions to provide the first complete Devonian succession from Celtiberia. He also attempted an integration of Rhenish (neritic) and Bohemian (pelagic) biostratigraphies based on evolution of different lineages (mainly brachiopods, trilobites, conodonts, dacryoconarids and goniatites). Based on these descriptions, he provided his conclusions on palaeogeography and tectonic evolution of SW Europe and NW Africa challenging plate tectonics interpretations for the Devonian of Europe. This aspect was previously outlined (Carls, 1982) and further developed in Carls (2003). The latter paper provides solid palaeozoogeographic arguments to contest the Tornquist's Sea and the Rheic Ocean as wide oceans and also challenges plate kinematics for Perigondwanan microcontinents. Palaeozoogeographic connections between the Iberian Chains (and Ibero-Armorica) and the Rhenohercynicum were already demonstrated for the Pragian (Middle Siegenian) (Carls and Valenzuela-Ríos, 1998). Further arguments supporting continuity of SW Europe sedimentary basins between Armorica and the Iberian Chains during the Upper Silurian and Lower Devonian (Pridoli-Pragian) were also provided (Carls and Valenzuela-Ríos, 1999) and were subsequently augmented with analysis of ostracods (Dojen, 2005) and fish remains (Dupret *et al.*, 2011) (see below under Stop 2).

At the change of Century, several papers provided new information and summarized accumulated knowledge on Devonian Stratigraphy and Palaeontology (Carls, 1999; 2002; Carls and Valenzuela-Ríos, 2002a). Below, we adapt these data, combined with new ones (e.g. Gozalo *et al.*, 2017; Villas *et al.*, 2018) to give fieldtrip participants a quick view of the main features of the Devonian strata in the Iberian Chains.

Devonian rocks crop out in five main areas (Fig. 38; Carls, 2002; Carls and Valenzuela-Ríos, 2002a), being the Axial Depression of the Río Cámaras (ADRC) the largest and more important one for the Lower and Middle Devonian. The Nigüella area supplies relevant data on Lower Devonian faunas (Carls and Valenzuela-Ríos, 1998; Valenzuela-Ríos, 1984; 1989), which are important for the aforementioned palaeogeographical connections between the Iberian Chains and the Rhenohercynicum. The Montalbán Anticline exposed Middle Devonian and Upper Devonian rocks; however, the latter are only partly known from several disconnected sections (Carls 1988, 2002; Carls and Lages, 1983; Carls and Valenzuela-Ríos, 2002a). The Tabuenca area exposes about 1,300 m of continuous Upper Devonian siliciclastic rocks (Carls, 1988; Gozalo, 1984; 1994; Gozalo *et al.*, 2001; 2017).

These five areas provide numerous, short, partial sections that, however, are detailed subdivided by the rich fossil content they hold and accurately correlated to build up the stratigraphic succession, which is close to 4,000 m (Fig. 39). Most of the rocks are siliciclastic (shales, clays, sandstones and orthoquartzites), carbonate rocks are common but thinner (limestones and marls). The Devonian sequence was mainly deposited in a shallow neritic marine environment and most strata are fossiliferous. In certain cases, black shales and limestones record pelagic faunas with a high potential for correlations between neritic and pelagic environments. The correlations were mostly based on conodonts, brachiopods, trilobites, dacryoconarids, ostracods and ammonoids.

In the ADRC, Nigüella and Montalbán Anticline areas the following Pridoli (Silurian) to Upper Devonian formations can be recognised (Fig. 39): Luesma, Nogueras, Santa Cruz, Mariposas, Castellar, Ramblar, Loscos, Peña Negra, Molino, Monforte, Moyuela, Recutanda, Barreras, Salobar, Cabezo Agudo, Huesa, Bandera and Fuenpudrida. In the Tabuenca area the following Upper Devonian formations crop out (Fig. 39): Rodanas, Bolloncillos, Hoya and Huecha Seca. As depicted in Fig. 39, the succession in the ADRC and Montalbán Anticline shows some gaps of information between Ramblar and Loscos Fms., upper and

lower limits of Bandera Fm., between Cabezo Agudo and Huesa, Huesa and Bandera and Bandera and Fuenpudrida Fms. Between these two formations, but disconnected to them, strata assigned to the Lower Kellwasser Kalk are recorded (Carls and Lages, 1983).



Figure 40. Field aspects of Bádenas and Luesma Fms.; Las Viñas section. A. Shales of s3e with few sandstone beds. Bádenas Fm. B. Base of Luesma Fm. (d1a α); continuous thick orthoquartzite across the river. On the right down corner upper shales of s3e. C. View of member d1ay; shale-sandstone intercalations of Silurian age. Luesma Fm. D. Sand-orthoquartzitic thick banks of d1b β with iron and trace fossils. Luesma Fm. Uppermost Silurian? E. Carbonatic levels in the upper part of Luesma Fm. (d1cy). Lower Lochkovian. Early Devonian. F. Detail of D.

During the fieldtrip we will examine Pridoli and Early Devonian strata in two set of outcrops: 1) Las Viñas Section and 2) South of Barranco de Santo Domingo. Both areas provide an excellent overview of the neritic environments developed during the Early Devonian with their excellent fossil record composed mainly of brachiopods, trilobites, cephalopods, crinoids, conodonts, ostracods, pelecypods, dacroconarids, solitary and colonial rugose corals and tabulates, fenestellid and ramose bryozoan, gastropods, and vertebrates (fish remains). Local sea-level pulses and sedimentary rhythmicity are demonstrated through the sequence. Macro plant remains, spores and algae lamination are also recorded in the Noguerras Fm. The former record suggests occasional emersion due to local replenishment of intertidal environments (Carls, 1988).

STOP 12: Pridoli (Silurian) to Emsian (Lower Devonian) marine communities from Las Viñas section.

Location

The section mostly crops out along the former path to Virgen del Carmen mine pit that runs parallel to the Cámaras river southwest of Santa Cruz de Noguerras. (Figs. 38, 39)

Coordinates: 41°6'46"N, 1°7'22"W, Geological map of Spain, 1:50,000, sheet Moyuela (466)

Geological setting: Herrera Unit (Eastern Iberian Chain); West Asturian-Leonese Zone.

Lithostratigraphic units: Bádenas, Luesma, Noguerras, Santa Cruz and Mariposas formations (Figs. 38-42).

Age: Pridoli-Emsian (Late Silurian-Early Devonian).

Aims

Observe the general and main features of the Pridoli and Lower Devonian strata and macro faunas in the Iberian Chains. Discuss about the local sea-level changes associated to vertical movements of the Cantabro-Ebroic Massif and their effect in vertical variations of environments and marine communities. Show the approximate location of the Silurian/Devonian boundary and of the Lower Devonian Stage boundaries with special focus on the base of the Emsian, after the ongoing redefinition by the International Subcommittee on Devonian Stratigraphy (SDS).

Description

The section Las Viñas shows an almost continuous Late Silurian and Early Devonian succession, which is unique in the entire Iberian Chain. Its thickness is about 800 m and almost all the section is overturned. Parts of the section are faulted, which slightly decrease the thickness of these intervals. Also, in some cases, a few strata are covered in the section, but they can be followed uphill in the nearby fields. The section starts in the right bank of the Cámaras River with good outcrops of the Bádenas Fm. and the contact between the Bádenas and the Luesma Fms. After crossing the river, the section continues on the left bank of the river, along the dirty path; there, the Luesma, Noguerras, Santa Cruz and the basal part of the Mariposas Fm. can be studied. After crossing the river again and moving eastwards across the former local road TE-V-1521, the lower part of the Mariposas Fm. crops out.



Bádenas Formation

The Bádenas Fm. (Figs 40A-B) consists of about 1,400 m of black shales with sandstone and orthoquartzite intercalations, which were deposited mostly in shallow waters from the late Llandoveryan to the late Ludlovian (Carls, 1988); it has been further subdivided into five members, s3a-s3e (Carls, 1965). The arenaceous/orthoquartzitic s3d member was visited the first day (Las Bruterías section) and is described there. Las Viñas section exposed the s3d with rich faunas of *Baturria edgelliana simonae* (Fig. 44 P, R-T) and the s3e members. In this outcrop we will examine the s3e member (Fig. 40A). The s3e member is the youngest one and it consists of about 150 m of shales with some sandy beds intercalations. Fossils are not abundant and restricted to the arenaceous beds; trace fossils are common. In the upper part *Monograptus fritschi linearis* has been recorded. Also small orthoceratids, few Pteriacea, few specimens of gastropods, many Rhynchonellacea, Chonetids, scarce Dalmanellacea and small rests of Euryptoids have been found in other sections.

Regarding its arenaceous content the s3e member is further subdivided into three parts (α - γ), bearing alpha and gamma more sandy beds. We will visit the s3e γ in Las Viñas section. There, it is 50 m thick and exposes sandstone, orthoquartzitic and shale beds. The sandy and quartzitic beds recorded graptolites, brachiopods and trace fossils.

Luesma Formation

The Luesma Fm. (d1) has a thickness of about 225 m and is subdivided into three members (d1a-c) (Figs. 40B-F). It comprises uppermost Ludlow?, Pridoli and part of the Lower Lochkovian. The Silurian/Devonian boundary is placed in the second member (d1b). Each member starts with white thick-bedded orthoquartzite fining upwards into alternation of shale and sandstone/orthoquartzite. The frequency and diversity of the fauna and the variety of sediments increase upwards, including some iron oolites, phosphoritic intraformational conglomerates, microconglomerates, impure sandstone and arenaceous shelly limestone. The uppermost 13 m of orthoquartzites (unit d1c γ) contain thin carbonate beds, lumaquelles, phosphate and the richest fauna of the whole formation (Fig. 43 O, AA-AC, AF-AI. Fig. 44 A, B, D-G. Fig. 46 Y). In the Viñas section parts of d1b are covered, mainly the upper part. Also, the d1c γ unit is partially disrupted by tectonics.

The basal member (d1a) (Fig. 40B) is thicker than the other two and contains Silurian guide fossils. Phosphoritic pebbles are common in d1a β and d1a δ units, which are sandy/quartzitic members with local accumulation of bad preserved fossils. Among them, the following were listed (Carls, 1965; Carls and Valenzuela-Ríos, 1999): abundant *Leptostrophia* sp. B *sensu* Carls, *Salopina missendenensis*, *Plethorhynchia*, "*Dalmanella*" cf. *basalis*, "*Camarotoechia*" sp. and Pteriacea; scarce *Chonetes* sp., orthoceratids, big tentaculites and crinoid remains. In other nearby localities, a few trilobite remains and ostracods were also recorded. The arenaceous shales and sandstones of the uppermost unit (d1a ϵ) bear fossil burrows.

The middle member (d1b) is subdivided into two parts (α and β). The d1b α unit contains abundant trace fossils and *Grammysia* sp.; few Rhynchonellacea are also recorded. A few meters above the base of the d1b β unit an oolitic iron horizon of about 1m thick with poor fauna occurs (?Acanthodii, "*Camaro-*

Figure 41. Field aspects of Noguerras and Santa Cruz Fms. A. View of d2a α , thick beds of shelly limestone with bryozoan and crinoids; Lochkovian. Early Devonian. B. Upper beds of the Noguerras Fm.; d2c. Pragian. Early Devonian. C. Partly covered and faulted contact between Noguerras and Santa Cruz Fm. Pragian. Early Devonian. D. Upper beds of Santa Cruz Fm.; d3c with ferruginous quartzites. Pragian. Early Devonian. E. Intertidal oscillation ripples in the upper part of the Santa Cruz Fm. (d3c). Pragian. Early Devonian. F. Detail of E.



Figure 42. General aspects of the Mariposas Fm. lower parts Pragian/Emsian transition. A. General view of the youngest part of Las Viñas section (yellow bars). The section ends at the old bridge, with the contact between the Santa Cruz (d3) and Mariposas (d4) Fms, which can be followed along a large area (white line). The second yellow line corresponds to the outcrop “Carrabádenas” and represents the stratigraphic continuation of Las Viñas section. B. View of the lower limestone beds of Mariposas Fm. (d4a α). Pragian/Emsian transition. Roadwork has affected this classical locality “North of Nogueras”. C. View of shale dominant d4a β in Carrabádenas outcrop.

toechia" *nucula* and bivalves). Above, the shale-sandstone intercalation bears many trace fossils. Abundant *Platyorthis* sp. D. e.g. *monnieri*, *Pododella rensseleeroides*, *Acastella heberti* (Fig. 46 X,W,Z) and *Howellella mercurii* in the upper part of this member (Fauna d1bβ2) suggest that the base of the Devonian is within the upper half of d1bβ. Besides, *Iridistrophia* sp., *Alatiformia?* sp., *Actinopteria* sp., *Grammysia* sp., Homalonotidae, "*Tentaculites*" sp., ostracods, conodonts (Fig. 43AD, AE) and crinoids are recorded as well.

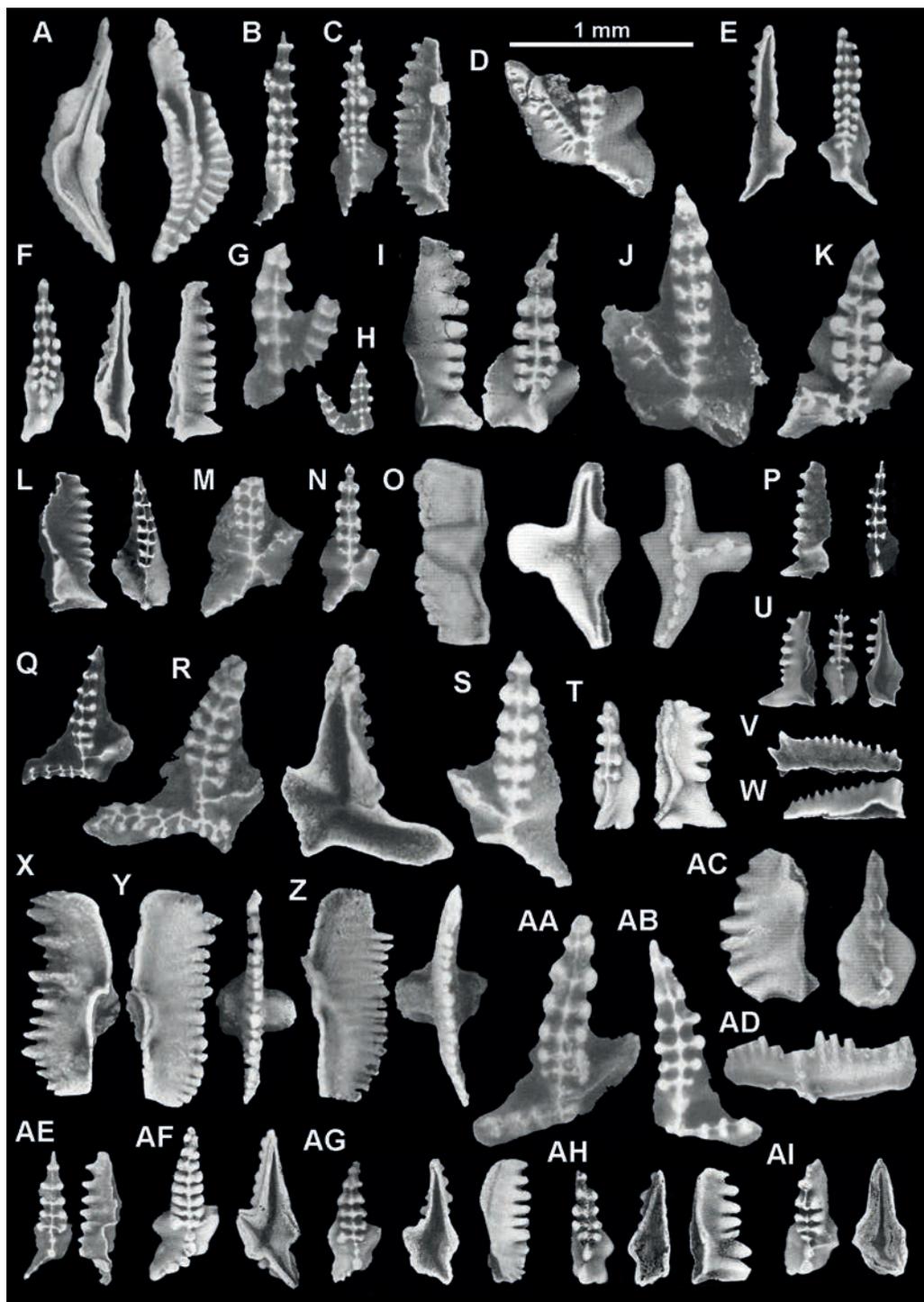
The upper member (d1c) has greater fossil diversity and a thick carbonatic level in the upper part (d1cγ) (Fig. 40E), which has furnished the more varied and riches fauna of the Luesma Fm. (for a detailed description of the faunal content refer to Carls and Valenzuela-Ríos, 1998). A few meters above the basal quartzites of this member (unit d1cα), within the overlain sandstone/shale alternation a new shelly fauna enters: *Howellella* (*Hysterohowellella*) *knetschi* and *Baturria pini* (Fauna d1cα1) (Fig. 44 J, L-Q). Upper beds of this lower quartzitic member (d1cα) are characterized by massive bryozoan colonies. The d1cβ yielded *Tentaculites* sp., *Grammysia* sp. and *Nuculites* sp. The upper unit (d1cγ) consists of quartzitic sandstones, arenaceous shales, calcareous sandstones and arenaceous shelly limestones with patches of bryozoan colonies and constitutes the transition to calcareous sediments. Phosphatic nodules are common. The rich fauna is composed of brachiopods, bivalves, trilobites, conodonts, tentaculitids and fish scales. Among them, the following are noteworthy: *Platyorthis* sp., *Proschizophoria falsa interpres* (Fig. 44 A,B,D,F,G), *Schizophoria runegatensis*, *Mclearnitesella lecaroensis*, *Geniculomclearnites levicaudata*, *Boucotstrophia?* sp., *Iridistrophia* sp., *Uncinulus* sp., *Protathyris* sp., *Anathyris* e.g. *undata*, *Howellella* (*Hysterohowellella*) *cortazari* (Fig. 44 H). Besides, the fauna includes Homalonotidae, Dalmanitacea, *Acastella* spp., ostracods (*Ulrichia*, *Cytherellina*), *Orbiculoidea* sp, lingulids, "*Tentaculites*" sp., *Aulopora* sp., *Actinopteria* sp., *Nuculites* sp. Microfossils are also abundant (conodonts, phyllocarids, conularids and microichthyoliths): *Zieglerodina remscheidensis*, *Z. repetitor*, *Ancyrodelloides carlsi*, *Icriodus woschmidti*, *I. transiensis*, *I. bidentatus*, *I. rectangularis*, *Pelekysgnathus elongathus* and *P. serratus* (Fig. 43 O, V-Z, AA-AC, AF-AI).

After the Luesma Fm., the sand supply abruptly stopped leading to the formation of shelly limestones and shales of the Nogueras Fm.

Nogueras Formation

The Nogueras Fm. (d2) measures about 140 m and is subdivided into three members (d2a-c) (Figs 41 A-B). It yields a wealthy palaeontological record that permits identify the Lochkovian/Pragian boundary within the d2b member. This formation consists of shelly limestone, marl, siltstone and occasionally sand lenses (palaeochannels) or more continuous thin beds, which mostly correspond to lag deposits, interbedded between shales. Several small faults affecting the section Las Viñas impede a continuous and complete examination of the Nogueras Fm. Besides some short intervals are currently also covered. Observations can be completed on the other side of the river and along the hill north of the section. Additionally, excellent outcrops of this formation can be studied in the adjacent Nogueras-Santa Cruz de Nogueras area.

The d2a consists of about 30 m of dominant shelly limestone beds with few thin shale beds interbedded in the upper half. Accordingly, it can be subdivided into two parts, the lower one, d2aα (Fig. 41A), with thick limestone beds (up to 30 cm), iron oolites and phosphatic pebbles and very thin (if any) shale interbeds, and the upper d2aβ with shales interbedded with thinner limestone and marl beds. All the beds are rich in fossils, mainly brachiopods. Thick limestone beds of d2aα are rich in colonial-bryozoan and crinoidal broken remains; tabulate corals are also present; however, preservation, especially of shelly components, is poor. Upper calcareous beds of d2aα increase the mud content (marl to marly limestone).



Thickness of d2a β , is tectonically reduced (faulted) in section Las Viñas to 4 m (other sections show a thickness about 15 m). Fossils are better preserved than in the underlain d2a α , many brachiopods with both valves together, accumulations of *Tentaculites* are common, and, in some cases, ostracods as well; phosphoritic pebbles and fish remains are also recorded from d2a β . The conodonts *Icriodus lotzei* (Fig. 43 Q, R), *I. vinearum* (Fig. 43 M, N, S) and *I. fallax fallax* (Fig. 43, D, J) enter in d2a. Brachiopods are abundant, being the more important *Playorthis* sp., *Proschizophoria falsa* (Fig. 44 C), *Schizophoria* sp., *Mcleanitesella* sp., *Iridistrophia* sp., *Anathyris* e.g. *undata*, *Mutationella* e.g. *barroisi*, and *Cryptonella?* spp.; *Howellella* (*Hysterohowellella*) *lunae* in d2a β follows *H. (Hy.) cortazari* from d2a α (Fig. 44 I). Other common fossils are *Actinopteria* spp., *Platyceras*, *Bucanella*, *Parahomalonotus*, *Acastella* spp. (Fig. 46 P,Q,U,V,Y,AA). Crinoids and asterozoan remains. Less frequent Chaetetids, *Aulopora* and the brachiopods *Dichozygopleura*, *Guaxa*, *Uncinulus* and other rhynchonellids. In some concrete levels higher diversity of certain groups is recorded: the bivalves, *Nuculites* spp., *Palaeoneilo*, *Leiopteria*, *Paleopecten*, *Grammysia*, *Goniophora* and *Modiolopsis*; ostracods, phylocarids and fish remains, including placoderms. Frequent bonebeds containing Acanthodian scales and spines and teeth of elasmobranchian (*Leonodus*) are recorded in the upper half of d2a.

The d2b is about 20 m thick and is composed of dominant shales with some fine grain sandstones and few limestone beds. Two parts are distinguished (α and β); the boundary between them coincides with a thick (35-50 cm) sandy-mudstone dark-brown bed (Bed A), which contains the Pragian index *Vandercammenina sollei* (Fig. 45 A). Therefore the d2b α /d2b β boundary coincides with the base of the Pragian. The unit d2b α consists of shales with sandy palaeochannels, coquina limestone, iron oolites and some phosphatic pebbles. These late Lochkovian strata bear *Cryptonella*, *Hysterolites gandli* (Fig. 45 D), *Schizophoria* n. sp. w, uncinulids, bryozoan, tabulate corals. The upper part of the Bed A yielded, besides *V. sollei*, a rich fauna with *Schizophoria* n. sp. b, *Trigonirhynchidiidae* and fenestellid bryozoan. The d2b β contains a few thin limestone beds intercalated with dominant shales and sandstones. New income of faunas is limited; we can mention the following taxa: *Icriodus castillianus* (Fig. 43 I), *Vandercammenina ovetensium* (Fig. 45 B), *Hysterolites gandli* and *Chonetes pinguis*. This member is partly faulted and covered in Las Viñas section.

The exposed d2c in Las Viñas section measures about 25m (Fig. 41B), representing a reduced thickness with respect to other localities (about 40 m); this is probably due to tectonics (faulting). It is composed

Figure 43. Conodonts from the Luesma, Nogueras, Santa Cruz and Mariposas Formations. A. *Polygnathus excavatus*; Holotype, basal bed d4a α . Lower and upper views. B, C. *Icriodus curvicauda* d3b; B, upper view; C, upper and lateral views. D, J. *Icriodus fallax*; D, upper view, Holotype d2a β ; J, upper view d2a α ; Las Viñas section. E, F. *Icriodus cellibericus*; d4a α ; Carrabádenas section. E, lower and upper views; F, upper, lower and lateral views. G, H. *Icriodus fallax* G; upper views of elements around the Lochkovian/Pragian boundary. I. *Icriodus castillianus*; lateral and upper views of Holotype. Around Lochkovian/Pragian boundary. K. *Icriodus simulator*; upper view of holotype; lower Pragian. L, P. *Icriodus alcoleae*; L, lateral and upper views of holotype; P, lateral and upper views. Lochkovian. M, N, S. *Icriodus vinearum*; M, upper view of holotype; N, S upper views of paratypes. All from d2a α , Las Viñas section. O. *Ancyrodelloides carlsi*; lateral, lower and upper views; d1c γ . Q, R. *Icriodus lotzei*; Q upper view of holotype; R upper and lower views of paratype. Lochkovian. T, U. *Icriodus angustoides*; T, upper and lateral views of holotype, d2a α ; U, lateral, upper and lower views of a Pragian specimen. V, W. *Pelekysgnathus elongatus*; lateral views of Lochkovian specimens. X, Y, Z. *Zieglerodina repetitor*; X, lateral view; Y, lateral and upper views; Z, lateral and upper views. Lochkovian specimens. AA, AB. *Icriodus rectangularis*; upper views of specimens from d1c γ ; AB from Las Viñas section. AC. *Pelekysgnathus elatus*; lateral and upper views of holotype; d1c γ . AD. *Zieglerodina remscheidensis* 40; lateral view; d1b β ; lowermost Lochkovian. AE. *Icriodus woschmidti*; upper and lateral views; d1b β ; lowermost Lochkovian. AF, AG. *Icriodus transiens*; AF upper and lower views of holotype; AG upper, lower and lateral views; both specimens from d1c γ . AH, AI. *Icriodus bidentatus*; AH, upper, lower and lateral views of holotype; AI upper and lower views; both specimens from d1c γ . All specimens are reillustrated from Carls and Gandl, 1969 (A, E, F, O, T, AC, AF, AG, AH, AI), Carls, 1969 (I, K, L, P, Q, R, U, V, W, X, Y, Z) and Carls, 1975 (B, C, D, G, H, J, M, N, S, AA, AB, AD, AE).

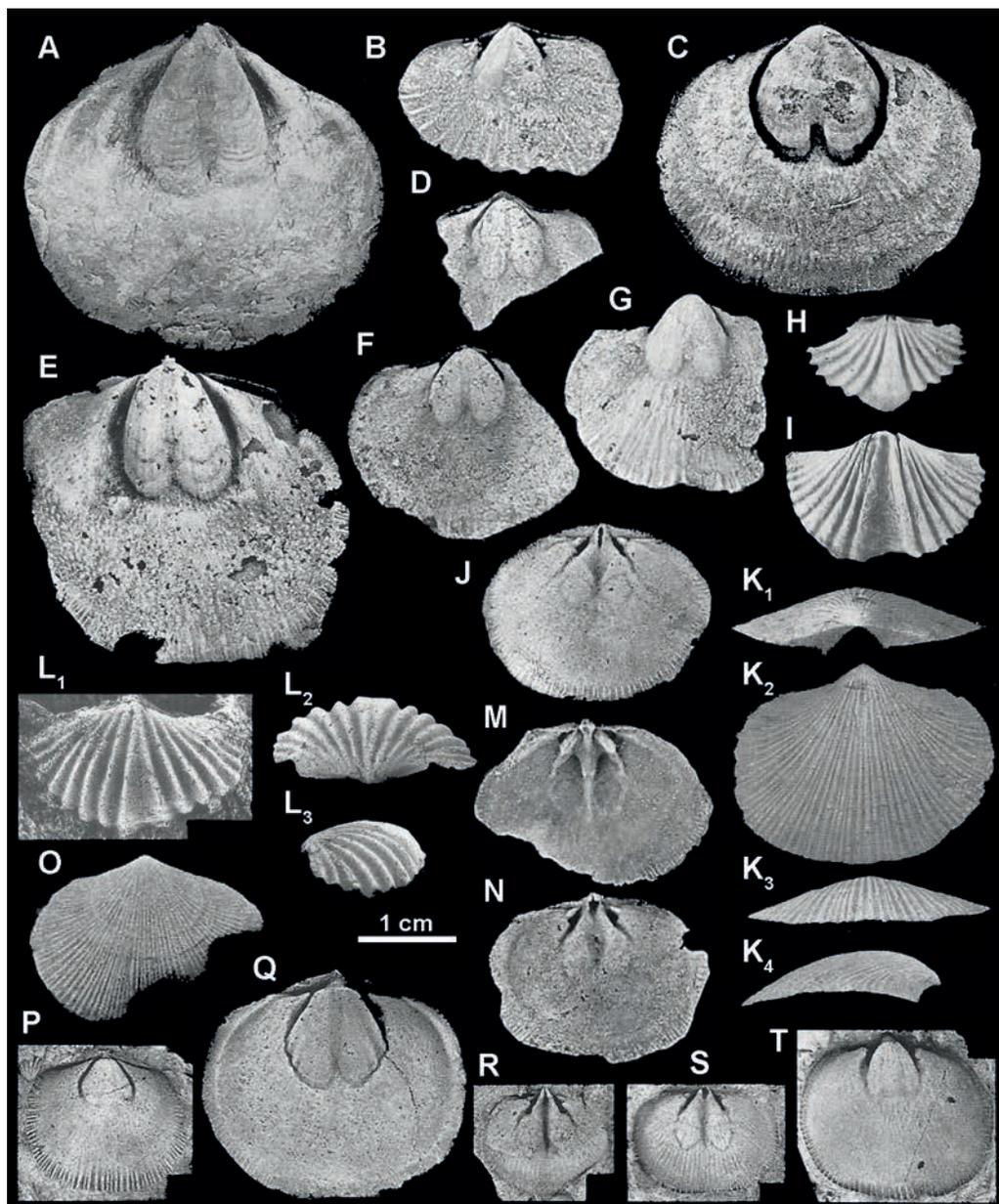


Figure 44. Brachiopods from the Bádenas, Luesma and Noguerras Formations. A, B, D, F, G. *Proschizophoria falsa interpres*; A. paratype d1cy Las Viñas section; B, D, F, G. paratypes from d1cy. C, E, K. *Proschizophoria falsa falsa*; C. holotype from d2aβ. E. paratype from d1cy Las Viñas section. K1-K4. different views of paratype from d2aβ, Las Viñas section. H, I. *Howellella cortazari* CARLS; H. paratype from d1cy. I. holotype from d2aα. L. *Howellella (Hysterohowellella) kenetschi*; L1-L3. different views of holotype (dorsal, posterodorsal and slightly oblique) d1ca1. J, M, O, Q, N. *Baturria pinni*; O. paratype (silicone mould). J paratype; M, paratype (silicone mould); Q. holotype; N. paratype. All specimens from d1ca. P, R, S, T. *Baturria edgelliana simonae*; all are paratypes from s3dγ, Las Viñas section. All specimens reillustrated from Carls 1969 (H, I), Carls, 1974 (A-C, D-G, J, K, M-T) and Carls, 1985 (L)

of an alternation of argillaceous limestone/ sandy marl and shales with abundant fossil remains. It can be subdivided into two parts, a lower one (d2c α) with thin beds rich in sandy components and an upper part (d2c β) with thicker "sand-free" beds. The d2c α starts with an almost monospecific fauna of *Platyorthis* e.g. *circularis*. Above follow *Mauispirifer* sp. H, *Plebejochonetes oehlerti*, *Fascistropheodonta*; in the upper part of this unit enters *Torosospirifer rousseaui* and *Icriodus simulator* (Fig. 43 K). The limestone and marl contain phosphatic pebbles, fish remains, algal lamination and beds of *Nuculites*. Sunburnt clay flakes

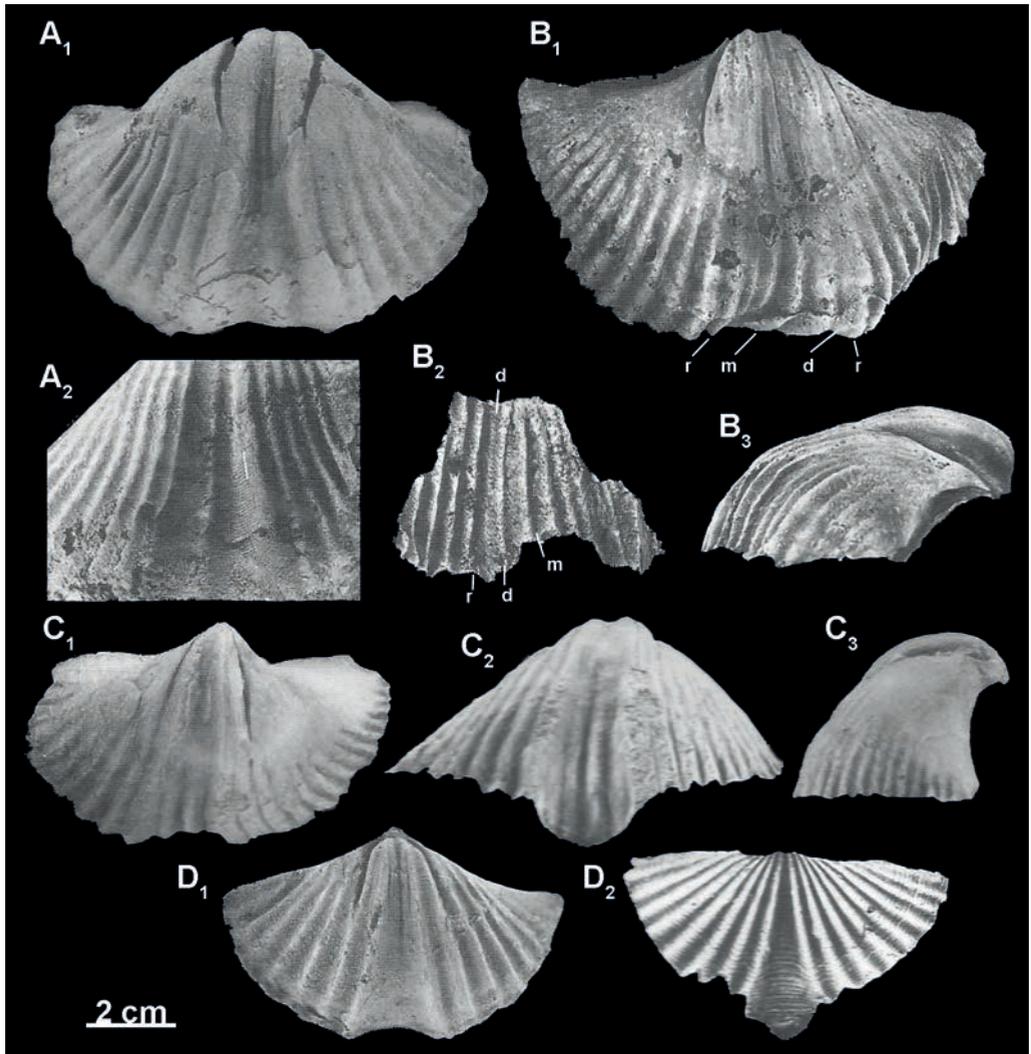
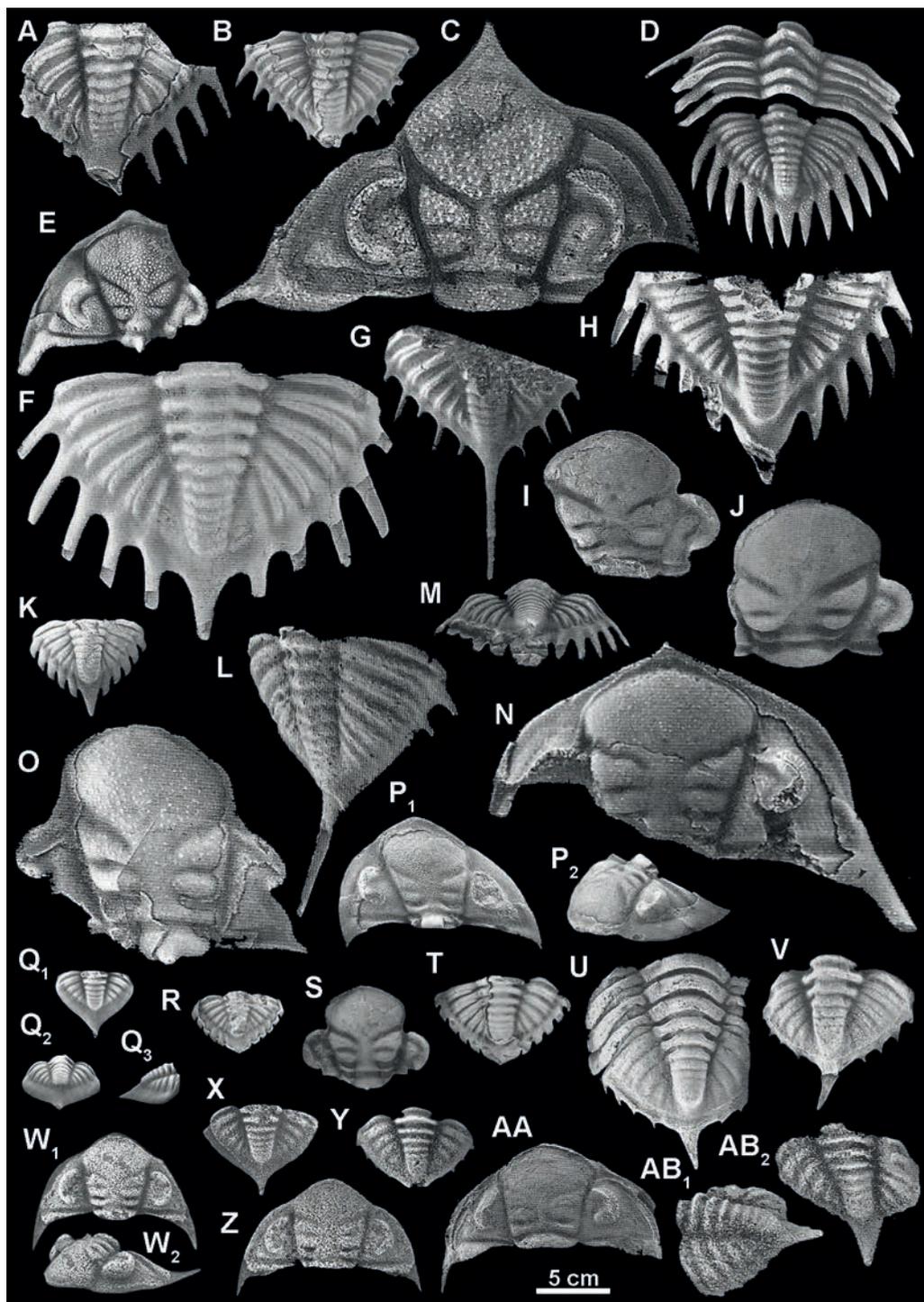


Figure 45. Brachiopods from the Nogueras Formation. A. *Vandercammenina sollei*, holotype; Bed A, base of d2b β 1; index of the base of Pragian in the Iberian Chains; A1. ventral view and A2. details of sinus and ribs. B. *Vandercammenina ovetensium*, holotype; B1. ventral valve, B2. impression and B3. view from right; d: sinus-rip; m: middle sinus-rip; r: sinus-rip margin. Lower Pragian. C. *Vandercammenina gaugeri*, holotype, C1. ventral valve with C2. front and C3. right views. Lower Pragian. D. *Hysterolites gandli*, holotype with two valves; Bed A, base of d2b β 1. All specimens reillustrated from Carls (1986).



are frequent atop of some beds. The beginning of d2c β represents the beginning of a deepening pulse (Valenzuela-Ríos and Carls, 1996; Carls and Valenzuela-Ríos, 2002a). The strata record brachiopods (with *Torosospirife rousseaui* as the dominant group), trilobites (*Pseudocryphaeus* (Fig. 46 R-T), *Parahomalotus* and few “*Phacops*”) ostracods, some bivalves (*Actinopteria*), bryozoan, solitary rugosa, massive and branching tabulate and orthoconic cephalopods. The famous Nogueras Fountain fauna, by the locality of Nogueras, belongs to the d2c β . Villas *et al.* (2018) provide a complete brachiopod list of the taxa recorded in this unit.

Santa Cruz Formation

The Santa Cruz Fm. (d3) is about 300 m thick and mostly consists of siliciclastic rocks (sandstone and shale) with few carbonate beds (Figs 41 C-F). It has been subdivided into three parts (d3a-c). Faults affect thicknesses of d3a and d3b members in Las Viñas section.

The lower member (d3a) is composed of fine argillaceous shales with small brachiopods, trilobites (Asteropyginae), ostracods and gastropods. It is further subdivided into three parts (α - γ). Carbonate levels (mostly marls) with shelly fauna (brachiopods) and corals (rugose and tabulate) characterize the middle part (d3a β). The basal marly bed records the entry of several brachiopods, *Plicanoplia aulerciana*, *Renaudia mainensis* and *Acrospirifer beaujeni*; the latter is the key taxon considered by Carls (1987) for redefining the beginning of the middle Sigenian, and therefore for tie correlations with the classical subdivision of the Devonian in the Rheno Slate Mountains region. In the upper marls of d3a β occurs the first *Euryspirifer* with an intrasinal costa (*Euryspirifer* n. sp. 1 of Carls 1987). These calcareous beds also furnished relevant conodonts (*I. curvicauda* (Fig. 43 B, C), *I. claudiae*). The upper shales of d3a γ register the entry of *Ctenochonetes aremoricensis*.

The middle member (d3b) is characterized by the development of rhythmothems (Carls, 1988), which consists of shelly (coquina) limestone beds deposited in shallow tidal environments followed by intercalation of limestone and marls with shales, then, dark fine shales indicates the maximum depth of the rhythmothem, which is overlain by alternation of sandstones and arenaceous shales indicating the return to intertidal environments. The calcareous levels at the base of these rhythmothems include phosphorite and

Figure 46. Trilobites from the Luesma, Nogueras, Santa Cruz and Mariposas Formations. A, B, G, O, L, N. *Protacanthina velillae velillae*; A, paratype; pygidium with rests of carapace; B, holotype; pygidium with rests of carapace; G, paratype; dorsal view of pygidium; O, paratype of incomplete cranium in dorsal view; L, paratype of big pygidium; N, paratype, incomplete cephalon in dorsal view. All from a level in the section “Bacho de la Velilla” correlatable with d2a α ; upper Lochkovian. C, F. *Metacanthina asnoensis*; C, holotype; cephalon; F, paratype; big pygidium. Both from d4a β . Emsian. D, E. *Kaysserops obsoletus*; D, holotype with pygidium and part of the torax; dorsal view; E, paratype, part of cephalon; dorsal view. Both from d4a β . Emsian. H, I, M. *Metacanthina triangularis*; H, holotype, dorsal view of pygidium; I, paratype, part of cephalon; M, paratype, pygidium, posterior view. All from d3b δ . Pragian. J, K. *Paracryphaeus jonesi*; J, dorsal view of cranium; K, complete pygidium. All from d2c β . Pragian. P, Q. *Acastella latimarginata*; P, paratype, cephalon in dorsal (P1) and oblique- lateral views (P2); Q, holotype, complete preserved pygidium in dorsal (Q1), posterior (Q2) and lateral (Q3) views. Both specimens from a level in the section “Bacho de la Velilla” correlatable with d2a α ; upper Lochkovian. R, S, T. *Pseudocryphaeus astrictus*; R, paratype, small pygidium with rest of carapace, dorsal view; S, paratype, cranium; T, holotype, complete pygidium, dorsal view. Specimen R from d3b γ ; specimens S and T from d3b δ . Pragian. X, W, Z. *Acastella heberti*; X, pygidium, dorsal view; W, dorsal (W1) and upper oblique frontal (W2) views of small cephalon; Z dorsal view of cephalon. All specimens from d1b β ; lowermost Lochkovian. U, V, Y, AA. *Acastella tiro*; U, Pygidium and part of torax in dorsal view; V, characteristic big pygidium in dorsal view; Y, dorsal view of pygidium; AA, cephalon in dorsal view. Specimen Y comes from d1c γ ; lower Lochkovian. The other three from d2a α ; upper Lochkovian. AB. *Acastella hollardi*, holotype, lateral (AB1) and dorsal (AB2) views of pygidium. Specimen comes from d2b β 1; lowermost Pragian. All specimens reillustrated from Gandl (1972).

abundant fish scales. Highest faunal diversity is recorded in d3b β with *Hysterolites crassicosta*, *Rhenosnelselaeria* sp. sp. eg. *strigiceps*, *Leptaenopyxis*, *Siberella*, rhynchonellids, *Eospirifer*, big “*Tentaculites*” sp. and orthoconic cephalopods. The calcareous sandstone of d3b γ is full of *Mauspirifer* n.sp.

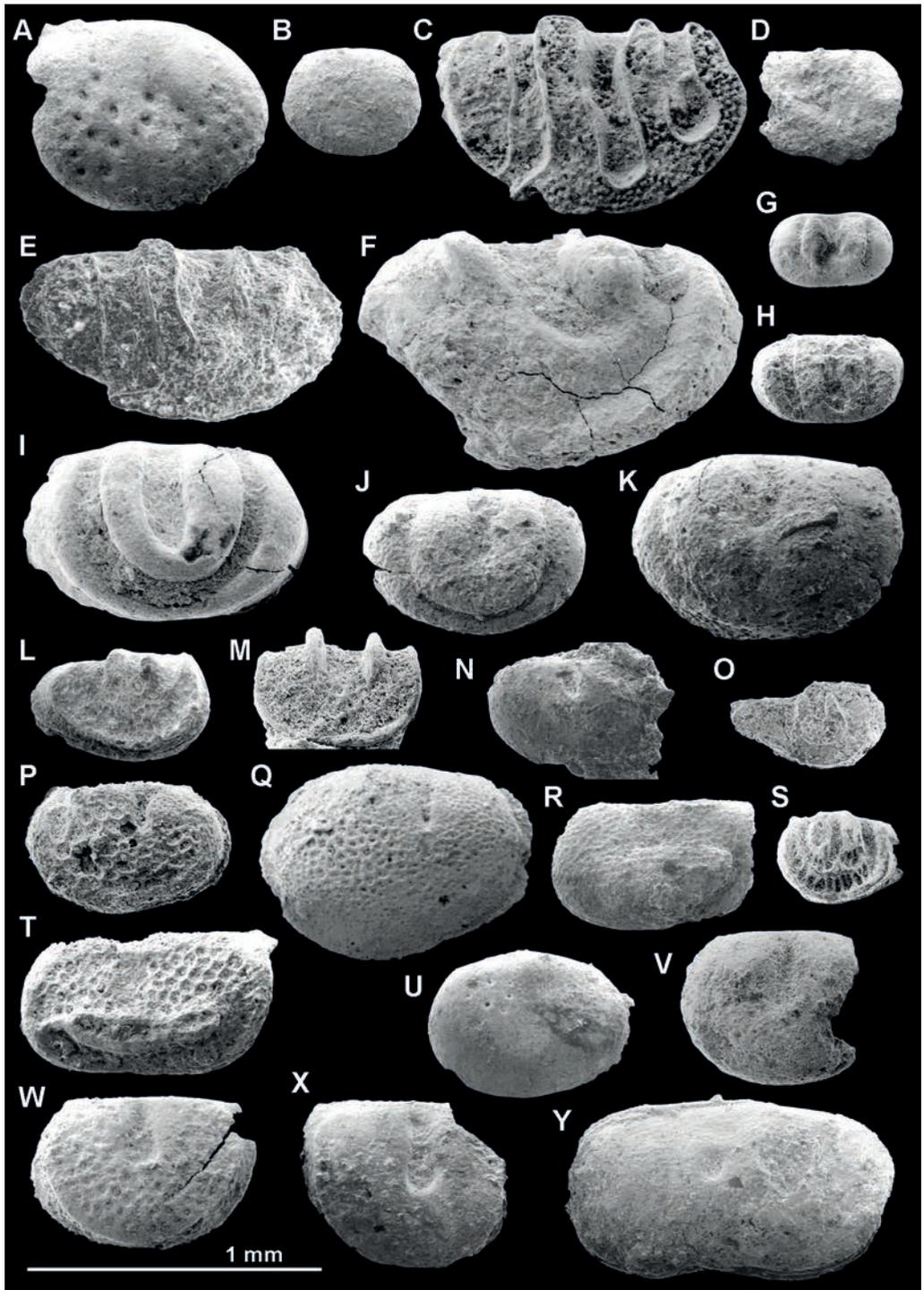
The upper member (d3c) consists of an alternation of sandstone and shale with abundant traces of *Zoophycus* deposited in intertidal environments (Fig 41 D-F). Also, some quartzite full of *Skolithos* were deposited. Most of this arenaceous member is barren of fossils, except for a few *Orbiculoidea* and poor plant and some fish remains in channel fillings (Carls and Valenzuela-Ríos 2002 b). At the top of the formation, this sandy-shaly intercalation grades through local iron oolites into a few meters of quartzite bearing a rich brachiopod and crinoid fauna (*Leptaenopyxis*, *Atrypa*, *Uncinulus*, *Vandercammenina*, *Crinistrophia*). In addition to, there are some tabulate and solitary rugose corals, bryozoan (both fenestellid and ramose), one scutellid pygidium and one “*Phacops* cf. *zinkenii*”.

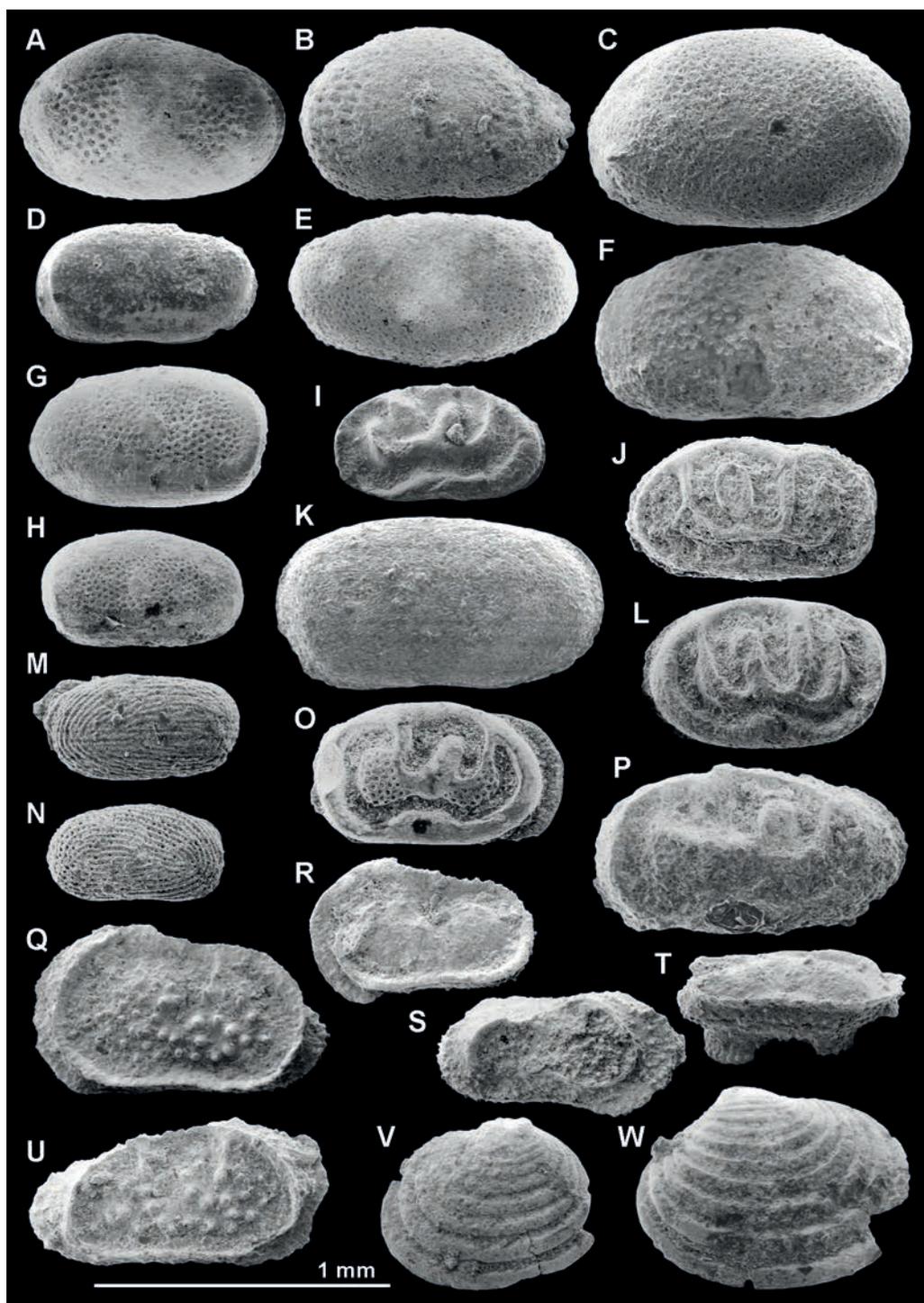
Mariposas Formation

The sand deposition ended abruptly and a shelly limestone started, marking the beginning of the Mariposas Fm. (Figs 42 A-C) which consists of 200 m of an alternation of shales and carbonates with rich faunas. The Mariposas Fm. is subdivided into two members (a and b), which are also further subdivided. In this fieldtrip we will only examine parts of the lower member (units d4a α and d4a β 1). Further lithological and faunistic description of the whole Mariposas Fm. can be found in Carls and Valenzuela-Ríos 2002a, b). The traditional German lower Emsian boundary is traced a little above the base of the Mariposas Fm., within the d4a β (Carls, 1987, 1988; Carls *et al.*, 2007, 2008; Carls and Valenzuela-Ríos, 1993, 2002a,b).

The Mariposa Fm. starts with 8 m of an alternation of shelly limestone, shale and bryozoan marl (d4a α) (Fig. 42B). The lower limestone beds contain abundant thick columnals of *Seiloucrinus verneuili*. The more common brachiopods are *Euryspirifer pellicoi*, *Arduspirifer* sp. 1, *Spinatrypa* and *Iridistrophia*. The presence of *Filispirifer fallax* is important for age assignment and correlation with the classical Emsian region in Germany. Also the tentaculitoids *Guerichina* and *Peneauia*, which are typical of late Pragian age in the original sense are common on these limestone beds. The basal limestone bed yielded the holotype of *Polygnathus excavatus excavatus* (Fig. 43A) and *P. excavatus* 114, which is the proposed biostratigraphical marker for redefining the base of the Emsian.

Figure 47. Ostracods from the Noguerras Formation. A. “*Aparchites*” ? sp. 1, unit d2c β 4, 7 m below top of unit d2c β 5; left valve; B. “*Aparchites*” sp., unit d2c β , + 7.25 m; left valve; C. *Ctenoloculina* cf. *cicatricosa*, unit d2c β 7, + 0.6 – 0.8 m; heteromorph right valve; D. *Tetrasacculus curtus*, unit d2c β 7, + 0.6 – 0.8 m; heteromorph left valve. E. *Ctenoloculina longivelum*; unit d2c β 7, + 0.6 – 0.8 m; heteromorph right valve. F. *Bollia lavibadia*; unit d2c β 6, + 0.3 m; right valve. G. *Bollia*? sp. 3; unit d2c β 7, + 0.6 – 0.8 m; right valve. H. *Bollia*? sp. 4; unit d2c β 6, + 0.3 m; right valve. I. *Bollia* aff. *ungula*; unit d2c β 1; right valve. J. *Bollia* sp. B; unit d2c β 6, + 0.3 m; left valve. K. *Bollia* sp., cf. *Bollia* sp. B; unit d2c β 6, + 0.3 m; left valve. L. *Ulrichia* (*Subulrichia*) cf. *fragilis*; unit d2c β 3, + 3 m; right valve. M. *Ulrichia* (*Ulrichia*) cf. *elegans*; unit d2c β 7, + 0.6 – 0.8 m; right valve. N. Palaeocopida, gen. et sp. indet. 2; unit d2c β 7, + 0.6 – 0.8 m; left valve. O. *Ulrichia* (*Subulrichia*) cf. *fragilis*; unit d2c β 7, + 0.6 – 0.8 m; right valve. P. *Placentella* aff. *heraultiana*; unit d2c β 7, + 0.6 – 0.8 m; right valve. Q. *Placentella* ? n.sp. 8; unit d2c β 7, + 0.6 – 0.8 m; right valve. R. *Berdanella* sp. K; unit d2c β 7, + 0.6 – 0.8 m; left valve. S. *Torella*? n.sp. 7; unit d2c β 4, 7 m below top of unit d2c β 5; left valve. T. *Refrathella* aff. *bissousensis*; unit d2c β 7, + 0.6 – 0.8 m; left valve. U. Palaeocopida, gen. et sp. indet. 5; unit d2c β 7, + 0.6 – 0.8 m; right valve. V. *Punctoprimitia africana*; unit d2c β 4, 7 m below top of unit d2c β 5 left valve. W. *Punctoprimitia europaea*; unit d2c β 7, + 0.6 – 0.8 m; left valve. X. *Punctoprimitia* aff. *europaea*; unit d2c β 7, + 0.6 – 0.8 m; left valve. Y. *Sulcella* (*S.*) *kloedenellides*; unit d2c β 7, + 0.6 – 0.8 m; right valve. All specimens figured herein are reillustrated from Dojen *et al.* (2004), from South Barranco de Santo Domingo section. All specimens in calcareous preservation.





The submember d4a β is 18 m thick and consists mainly of silty shales with subordinate marly brachiopod limestone beds in the upper half, which allows further subdivided into two parts d4a β 1 and d4a β 2; as aforementioned, we will only visit the shales of the d4a β 1 (Fig 42C). This lower unit contains brachiopods, solitary rugose and tabulate corals, ostracods and trilobites (Fig. 46 C-F). Among the former, the occurrence of *Arduspirifer prolatestriatus* is pivotal for tracing the traditional base of the Emsian in the ADRC.

STOP 13 Lochkovian and Pragian (Lower Devonian) terrestrial and marine communities from South Barranco de Santo Domingo

Location

This area is located about 2.3 km SW of Mezquita de Loscos (Figs. 38, 39)
 Coordinates 41°4'2"N, 1°4'56" W, Geological map of Spain, 1:50,000, sheet Moyuela (466)
 Geological setting: Herrera Unit (Eastern Iberian Chain); West Asturian-Leonese Zone.
 Lithostratigraphic units: Nogueras Fm. (Figs. 38, 39).
 Age: Lochkovian-Pragian (Early Devonian).

Aims

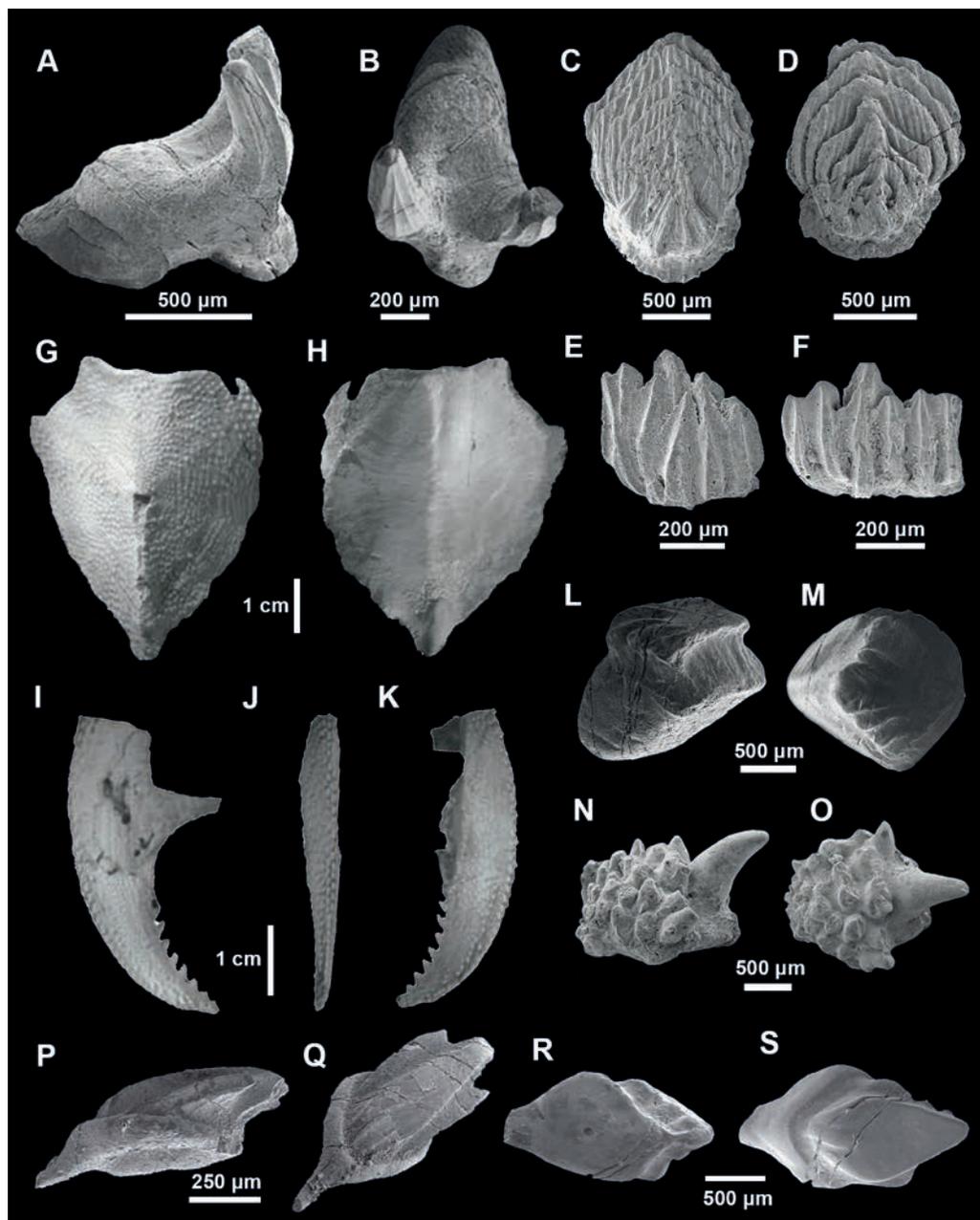
Observe details of the Nogueras Fm., in particular the members d2b, with the Lochkovian/Pragian boundary Bed and d2c, and in particular the different parts of the submember d2c β . Look at the particular beds where the invertebrates, vertebrates and plant remains come from. Discuss on environmental changes through the sedimentary sequence. Discuss inferences regarding paleogeographic affinities and reconstructions.

Description

Outcrops at the locality South Barranco de Santo Domingo do not show a continuous sequence through the Nogueras and Santa Cruz Fms., but partial sections are relatively easy correlated due to

Figure 48. Ostracods from the Nogueras Formation. A. *Bythocyproidea? polaris*; unit d2c β 4, 7 m below top of unit d2c β 5; right valve. B. *Punctomosea* sp. 29; unit d2c β 6, + 0.3 m; right valve. C. *Ponderodictya aggeriana*; unit d2c β 7, + 0.3 m; right valve. D. Thlipsuridae gen et sp. indet 2; unit d2c β 5, midpoint of unit; right valve. E. *Ovatoquassillites?* sp.; unit d2c β 5, 7 m below top of unit d2c β 5; left valve. F. *Ponderodictya inventeplicata*; unit d2c β 3, + 3.0 m; right valve. G. *Jenningsina?* n.sp. 14; unit d2c β 5, 7m below top of unit d2c β 5; left valve. H. *Jenningsina?* n. sp. 14; unit d2c β 5, 7 m below top of unit d2c β 5; right valve. I. *Polyzygia kroemmelbeini*; unit d2c β 2, 7.25 m above base of submember; right valve. J. *Polyzygia beckmanni antecedens*; unit d2c β 7, + 0.6 – 0.8 m; left valve. K. Thlipsuridae, gen et sp. indet 3; unit d2c β 5, midpoint of unit; right valve. L. *Polyzygia grekoffi*; unit d2c β 7, + 0.6 – 0.8 m; left valve. M. *Jenningsina* aff. sp. 28; unit d2c β 7, + 0.6 – 0.8 m; right valve. N. *Jenningsina thuringica*; base of unit d2c β 5; left valve. O. *Polyzygia normannica*; unit d2c β 5, 7 m below top of unit d2c β 5; right valve. P. *Polyzygia vinea*; unit d2c β 6, + 0.3 m; right valve. Q. *Leptoprimitia* cf. *ornata*; unit d2c β 7, + 0.6 – 0.8 m; left valve. R-T. *Zeuschneria* n.sp. 19; unit d2c β 7, + 0.6 – 0.8 m; 18, left valve; 19, right valve; 20, dorsal view. U. *Leptoprimitia balbiniensis*; unit d2c β 6, + 0.3 m; right valve. V. *Eridoconcha* sp. 23; unit d2c β 1, midpoint of unit; right valve. W. *Cryptophyllus?* sp., 1976; unit d2c β 1, midpoint of unit; left valve. All specimens figured herein are reillustrated from Dojen *et al.* (2004), from South Barranco de Santo Domingo section. All specimens in calcareous preservation.

both lithological guide beds and palaeontological content. The several sections cropping out in the south slope of the Barranco de Santo Domingo with the creek Regajo expose strata from Lochkovian to Pragian (Nogueras d2a β to Santa Cruz d3a β). The outcrops are tectonically affected by faults. Faunal content is rich and comprises many groups including, brachiopods, corals, fish remains, macroplants, spores, trilo-



bites, conodonts and ostracods. As a description of the Noguerras Fm. has been provided in the previous stop, we will comment herein on several fossil groups.

Guide Bed A, indicating the beginning of the Pragian, is observed close to bifurcation to “camino bajo”. *Leonodus carlsi* (semiarticulated specimen; see below) was found a few m above this level, in the shales of the submember d2b β 2. On this surface fish spines and plant remains can be observed.

Ostracods are common (Figs. 47, 48) in this locality and of great relevance for testing, or refuting, palaeogeographical hypothesis. Below Bed A, a slightly faulted succession comprising from the Lochkovian units d2a β 5 to d2b α 3, a rich ostracod sequence, has been documented (Dojen, 2005; Dojen *et al.*, 2004). They include “*Zygoberichia*” sp.sp., *Poloniella* sp., Eridostraca gen. et sp. indet. and smooth podocopids. Due to its size, “*Zygoberichia*” can be observed in many bedding planes. Above Bed A, on the south side of “camino alto” good exposure of d2c β furnished a rich ostracod fauna listed in Carls *et al.* (2003). Among them, the following genera are noteworthy *Ctenolocolina*, *Bollia*, *Ulrichia*, *Punctoprimitia*, *Ponderodictya*, *Jenningsinia*, *Polyzygia*, *Leptoprimitia*, *Zeuschneria*, *Eridoconcha* and *Cryptophyllus*. Dojen (2005) proved the great potential for ostracod-based Early Devonian biostratigraphy in Celtiberia, to this the records from the ADRC are pivotal. She proved that the Celtiberian ostracod faunas were related to other neritic ones from other parts of Europe and NW Africa, making a great contribution for a better understanding on the Early Devonian biogeographical relations between Gondwana and Baltica-Avalonia. In this sense, she refuted the ostracod-based arguments for the Rheic Ocean (compare Cocks and Fortey, 1982). Her data also corroborates the Ibarmaghian Faunal province previously depicted by brachiopods and trilobites. Finally, she provide enough information for supporting the continuity of the Ibero-Armorican through during the Pragian and challenged former opinions on biogeographical evidences for an open Early Devonian ocean between Ibero-Armorica and N-Africa (compare Tait *et al.*, 2000). On the contrary, the data she presented support the paleogeographical reconstruction of McKerrow *et al.* (2000) who postulated the proximity of Gondwana and Laurussia during the Early Devonian. This is further supported by the vertebrate records in the Iberian Chains (see below).

Early vertebrates remains have been documented in numerous Devonian outcrops of the ADRC including thelodonts, early condricthians, acanthodians, placoderms and basal osteichthians (Mader, 1986, Wang, 1993, Botella and Valenzuela-Rios, 2005). The study of vertebrate remains from these outcrops, after more than 60 year of intensive work initiated by Professor Peter Carls in the early 1960's, have shown their palaeobiological, phylogenetical, biostratigraphical and palaeogeographical relevance,

Figure 49. Devonian vertebrates from the Noguerras and Santa Cruz Formations. A, B. Teeth of *Leonodus carlsi* from the Noguerras Fm. (Lochkovian) Los Poyales section (MGUV-14861); A lateral view, B upper view. C, D. *Seretolepis elegans* from the Noguerras Fm., C, scale MPZ/2009–39 from the late Lochkovian, Los Poyales section; D. scale MPZ/2009–37 from the early Pragian of the South Barranco de Santo Domingo. E, F. *Altholepis composita*, E. Scale MPZ/2009–34 from the early Pragian of the South Barranco de Santo Domingo; F. Scale MPZ/2009–38 from the late Lochkovian, Los Poyales. G, H, I, J, K. Placoderm plates of *Kujdanowiaspis podolica* from the Noguerras Fm. (Lochkovian); G, H. median dorsal plate (specimen MPZ 2009/90) in dorsal (G) and ventral (H) views; I, J, K. right spinal plate (specimen MPZ 2009/98) in ventral (I), lateral (J) and dorsal (K) views. L, M, N, O. *Obruchevacanthus ireneae* from the Noguerras Fm., Upper Lochkovian, L, M. morphotype II (head?) scales (MGUV-21.329) in lateral view (L) and crown view (M) from Los Poyales; N, O. Spiral tooth (MGUV-21.332) in lateral (N) and occlusal (O) views from Maripló section. P, Q, R, S. Thelodont scales from Noguerras and Santa Cruz formations, Lockovian and Pragian. P, Q. Trunk scales of *Turinia nachoi* (MGUV 8106) in lateral (P) and crown (Q) views from Sur South Barranco de Santo Domingo, (Santa Cruz Formation, Pragian); R, S. Trunk scales of *Turinia pagei* (MGUV 8113) from basal (R) and crown (S) views from Las Viñas section (Noguerras Fm., Upper Lochkovian).

All specimens figured herein are reillustrated from Botella, 2005 (A, B), Martínez-Pérez *et al.*, 2010 (C, D, E, F), Dupret *et al.*, 2011 (G, H, I, J, K), Botella *et al.*, 2014 (L, M, N, O) and Botella *et al.*, 2006 (P, Q, R, S).

representing a great contribution for the understanding of the evolution and diversification of this group during the Devonian. One of the classical localities, South Barranco Santo Domingo yields abundant fish remains, which include dermal plates, tesseræ, scales, dermal denticles, jaws, spines and isolated teeth, those belonging to chondrichthyans represent ones of the most relevant.

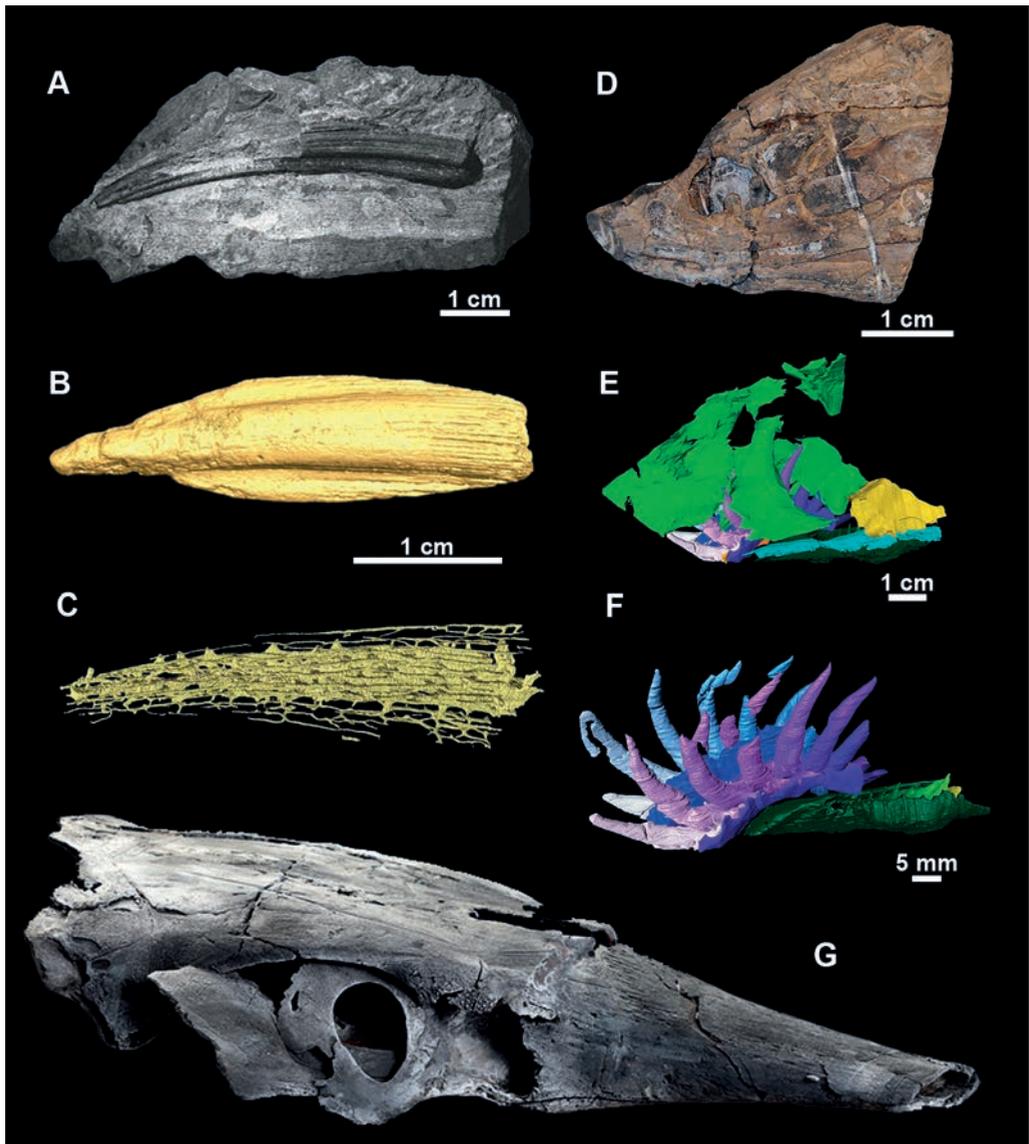
A large number of new early sharks have been described in the Early Devonian of Celtiberia; among these taxa, *Leonodus carlsi* (Fig. 49 A,B) stands out, constituting the oldest tooth-bearing shark known to date. The rich fossil record of this taxa, represented not only by isolated teeth, scales and spines, but also by one semi-articulated specimen (Soler-Gijón and Hampe, 2003), has allowed the reconstruction of its dental series and squamation, the estimation of their tooth replacement rates, and the establishment of the plesiomorphic condition of the oldest chondrichthyan teeth, in terms of morphology, tooth histology and vascular systems structure (Botella, 2006; Botella *et al.*, 2005, 2009a, b; Martínez-Pérez *et al.*, 2018). In addition to these findings, putative shark-like scales belonging to *Seretolepis elegans* (Fig. 49 C,D), *Altholepis composita* (Fig. 49 E-F) and cf. *Knerialepis mashkovae* from the Nogueras and Santa Cruz Formations support the relative proximity between Gondwana and Laurussia during the Lochkovian and early Pragian times and the existence of migration routes between the two continental margins (Martínez-Pérez *et al.* 2010). This idea has been subsequently supported by the description of other basal vertebrate groups in the Lower Devonian of Celtiberia, namely the small “actinolepids” placoderms *Kujdanowiaspis podolica* (Fig. 49 G-K) and *Erikaspis zychi* (Dupret *et al.*, 2011), which were considered until then endemic to Laurussia (Lochkovian of Podolia, Ukraine).

Acanthodians and Thelodonts microremains are also relatively well represented, with abundant, scales, dermal denticles, tesseræ, jaw bones, spines and isolated teeth. Thelodonts are abundant in numerous levels of the Nogueras and Santa Cruz Formations. The great morphological variation has allowed the identification of two taxa *Turinia pagei* in Lochkovian strata (Fig. 49 R, S), and *Turinia nachoi* in Pragian rocks (Fig. 49 P, Q), the latter possibly endemic from Celtiberia (Botella *et al.*, 2006). The record of both taxa includes cephalic, cephalopectoral and trunk scales. The associations of different Acanthodians bone elements (teeth, scales, spines, jaw bones and scapulocoracoids) distinguished two new species: *Obruchevacanthus ireneae* (Fig. 49 L-O) (Botella *et al.*, 2014) and *Machaeracanthus goujeti* (Fig. 50 A-C) (Botella *et al.*, 2012). The vertebrate fossil record is not exclusively limited to disarticulated elements from the Lower Devonian strata. The following articulated Middle Devonian vertebrates stand out. An almost complete skull of a new basal osteichthyan, *Grossius aragonensis* (Sarcopterygii) (Fig. 50D-F), and the emblematic “long-snouted” placoderm arthrodire *Carolowilhelmina geognostica*, both found in the Moyuela Formation (Eifelian) (Fig. 50G).

To date, the known Early Devonian plant fossil records from the Iberian Peninsula is mainly represented by poorly preserved remains with controversial taxonomic affinities, which do not allow a detailed

Figure 50. Devonian vertebrates from the Nogueras and Moyuela Formations. A, B, C. *Machaeracanthus goujeti* from the Nogueras Fm. (Upper Lochkovian). A. Spine of *Machaeracanthus goujeti*, paratype (morphotype 2) element MPZ 2009/28 in dorsal view where is clearly visible their longitudinal striated ornamentation, Maripló section (reillustrated from Botella *et al.*, 2012); B. surface render of a juvenile spine (morphotype 1) (MPZ 2010/950) from Maripló section in dorsal view. C. 3D vascular system reconstruction of a morphotype 1 spine (MPZ 2010/969) from Maripló section in dorsal view. D, E, F *Grossius aragonensis* (Gö 7091) a basal osteichthyan (Onychodontiformes (Sarcopterygii)) from the Eifelian (Middle Devonian) of the Moyuela Fm. D. Holotype deposited at the University of Göttingen in lateral view; E. volume segmentation of the anterior region of the skull after the CT scanning of the specimen; F. detail of the lower jaw. G. *Carolowilhelmina geognostica* Skull (Holotype MPZ 95/174). Lateral view of the skull with a total length of 43 cm. from the Middle Devonian of the Moyuela Fm. Picture from Dr. José Ignacio Canudo; originally illustrated by Carls (1995) and Mark-Kurik and Carls (2002).

study (Fig. 51). However, the outcrops of South Barranco de Santo Domingo documents several plant-bearing fossil sites with plant megafossils and/or dispersed spores from the Lochkovian-Pragian Nogueras Fm. Overall, the plant megafossils have been described as a basal euphyllphyte (Fig. 51A), a paired elongated sporangia (Fig. 51B) and *Taenioocrada*-like remains (Fig. 51C). According to Cascales-Miñana *et al.* (2015), they come from Member d2a. More than 20 spore genera have been also identified in the unit d2b β 2 (Cascales-Miñana *et al.*, 2016), including *Apiculiretusispora*, *Brochotriletes*, *Cirratiradites*, *Iberoespora*, *Knoxisporites*, *Latosporites* and *Verrucosisporites*, among others. Trilete spores mainly compose





the assemblage. Interestingly, specimens of *Latosporites ovalis* (Fig. 51D), a species previously reported only from late Pragian-early Emsian of Saudi Arabia and Brazil, are found in this assemblage, and probably represent the earliest known evidence of this species. Moreover, latest advances on the study of the Lower Devonian flora include the discovery of *Teruelia* (Fig. 51 E-H), a new basal land plant preserved as a compression fossil. *Teruelia* consists of isotomously branched robust stems terminated in large fusiform twisted sporangia. *Teruelia* morphology compares exactly with *Aglaophyton*, a permineralized early polysporangiophyte known up to now only from the Lower Devonian Rhynie Chert in Scotland (*Laurussia palaeocontinent*), which represents an early terrestrial hot-spring ecosystem. This fact suggests that at least one Rhynie Chert plant had a much wider distribution than previously known.

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Figure 51. Plant fossils from the Nogueras Formation. A. Plant megafossils attributed to basal euphyllophyte. B. A paired of elongated sporangia. C. *Taenioocrada*-like remains. D. *Latosporites ovalis*. E-G. Diverse aspects of the branched stems (E) ending in a large fusiform twisted sporangia (F, G). H. Reconstruction of *Teruelia* morphology. All specimens from South Barranco de Santo Domingo.

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**POST-CONFERENCE FIELD TRIP:
THE CENOZOIC PALEONTOLOGICAL RECORD FROM ALICANTE
PROVINCE (SOUTHEASTERN SPAIN): AN OVERVIEW**

POST-CONFERENCE FIELD TRIP - December 15th 2019:

THE CENOZOIC PALEONTOLOGICAL RECORD FROM ALICANTE PROVINCE (SOUTHEASTERN SPAIN): AN OVERVIEW

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Keywords: Tortonian, Messinian, Tyrrhenian, Bajo Segura basin, Betic Cordillera, paleoenvironments, coral reefs, ichnology.

INTRODUCTION

The itinerary runs through the Bajo Segura basin, one of the Betic Cordillera Neogene basins (Fig. 1). Its basement is conformed of metamorphic and sedimentary rocks from the two main domains of the Betic Cordillera: the Internal Zones (Alpujarride complex) to the south and the External Zones to the north. Tectonically and palaeogeographically, Bajo Segura basin has two clearly defined sectors, north and south (Corbí and Soria, 2016). In particular, the itinerary is focused in the northern sector of the basin where exceptional outcrops (some of them in the coast) can be appreciated. In this sense, two illustrative outcrops, recently studied in detail have been selected: the Cabo de la Huerta section (Giannetti *et al.*, 2019) and the Santa Pola Messinian coral reef (Corbí *et al.*, 2018). Indeed, these outcrops represent key examples of the rich and diverse Cenozoic geosedimentary and paleontological record of the Alicante province. Furthermore, both are two of the most popular sections employed in the outreach geological activities and undergraduate student field trips developed by the Earth Science Department of the University of Alicante. Additionally, and with the purpose to show the rich and diverse fossil record of the Neogene, the Paleontological Museum of Elche will be visited.

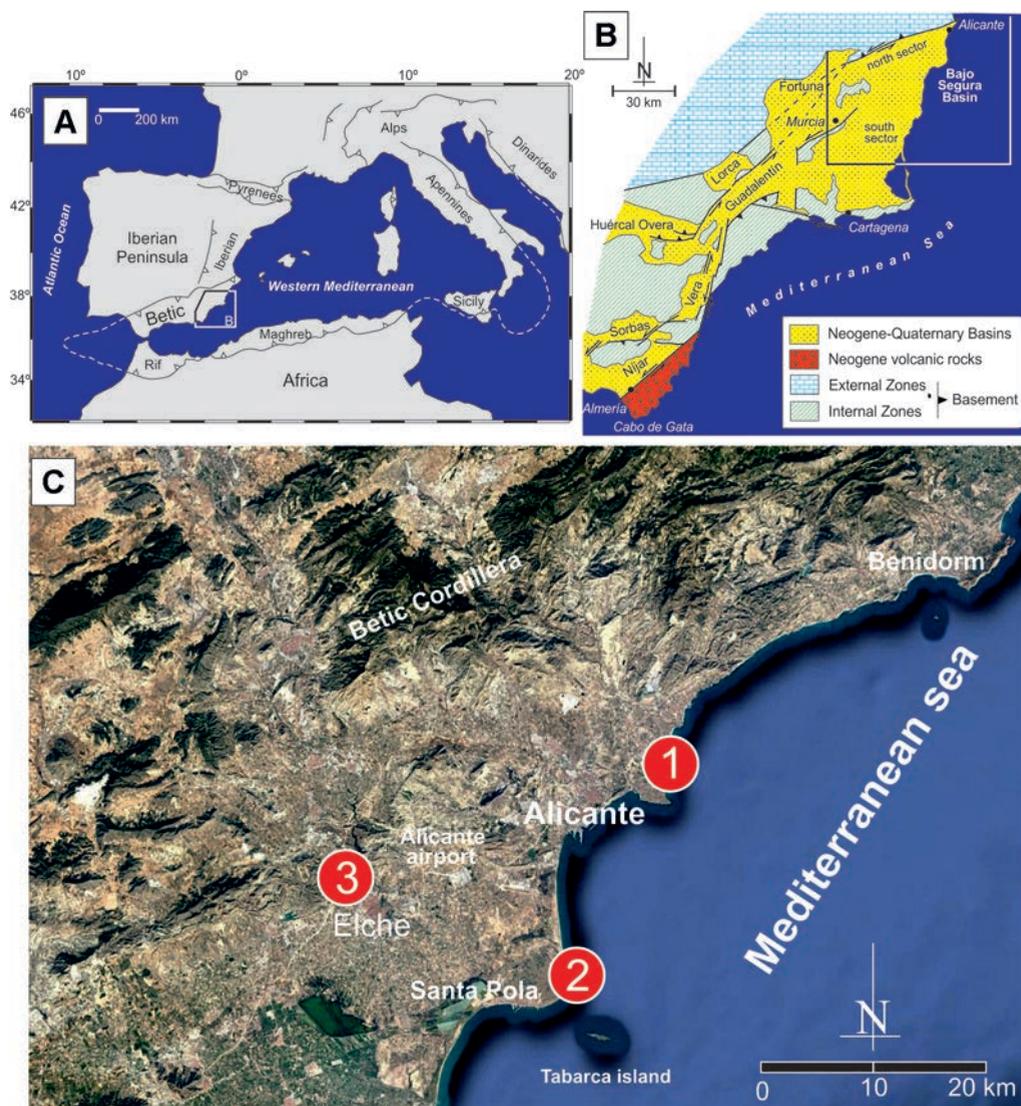


Figure 1. Geological context of the itinerary with the location of the three stops of the field trip. A: Location of the Betic Cordillera in the western Mediterranean. B: Geological map of the Eastern Betic Cordillera showing the location of the Bajo Segura Basin. C: Geographical context of the itinerary, indicating the position of the three stops. 1, Cabo de la Huerta section, located near the San Juan beach (Alicante). 2, Messinian Santa Pola coral reef (Santa Pola, Alicante). 3, Paleontological Museum of Elche (city of Elche). Modified from Corbí (2010).

STOP 1: Taphonomy, ichnology and palaeoecology in shallow-water settings (Cabo de la Huerta)**INTRODUCTION**

In the Cabo de la Huerta section (Alicante, Southeastern Spain, Figs. 2 and 3), Tortonian and Tyrrhenian deposits crop out, which record open-platform and coastal deposits respectively. Sedimentary structures are rare and bad preserved, so that ichnological, taphonomic, and palaeoecological analyses were integrated in order to determine the main processes involved in the material's sedimentation. The Cabo de la Huerta consists of a series of beds dipping north and forming small cliffs and abrasion platforms. The coastal geomorphology impressively enhances the stratigraphic, sedimentological, and palaeontological features of the beds, this being the main reason for the great pedagogical and didactic value of these outcrops. The aforementioned Tortonian and Tyrrhenian units belong to the Bajo Segura Basin (Alfaro, 1995), the largest of all the Neogene basins in the eastern Betic Cordillera. The Bajo Segura Basin formed as a subsident trough associated to the northern segment of the Trans-Alboran shear zone (De Larouzière *et al.*, 1988). It is filled by Tortonian to Quaternary deposits, which represent a great variety of facies, from continental to deep marine (Montenat *et al.*, 1990; Soria *et al.*, 2008; Caracuel *et al.*, 2011). Tortonian (unit 1) and Tyrrhenian deposits (unit 2) are separated by a clear angular unconformity, formed as a consequence of the folding of the Tortonian material. The Tortonian unit (Fig. 4) is mainly made up of interbedded coarse- and fine-grained calcarenites, whereas the Tyrrhenian material is represented by a variety of lithologies, from laminated, bioclast-rich microconglomerates at the bottom up to the silts and dune-shaped sandstones at the top of the section (levels 1 to 4 in Fig. 4).

Figure 2. Location of the Cabo de la Huerta study section (stop 1). Geological map modified from Pina and Cano (2004).



Location

Cabo de la Huerta, between the city of Alicante and San Juan Beach. (Fig. 3).

Coordinates: Latitude: 38°21'13.74"N Longitude: 0°24'14.82"W, Geological map of Spain, 1:50.000, sheet of Alicante (872).

Geological setting: Bajo Segura Basin.

Main topic: Event beds in shallow-water setting

Aims

Use of ichnological and taphonomical key features to determine event beds.

Overview of a transgressive episode as recorded in the Tortonian material.

Overview of a regressive sequence as recorded in the Thyrrhenian deposits.

Description

Tortonian Unit

The Tortonian beds are made up of interbedded fine-grained and coarse-grained calcarenites (Fig. 4).

Despite the great abundance of burrows, the diversity of trace fossils in the calcarenites is quite low, revealing depositional mechanisms and palaeoecological conditions limiting the development of a complex endobenthic tracemaker community. The ichnoassemblage is dominated by *Ophiomorpha nodosa* and secondarily by *Bichordites monastiriensis* (Fig. 5). These trace fossils use to be very common in high-energy event beds and shifting sands, as tempestites and deposits affected by longshore currents and wave motion, in shallow-water platforms (de Gibert and Goldring, 2007, 2008; D'Alessandro and Uchman, 2007; Aguirre *et al.*, 2010; Buatois and Mángano, 2011; Rajchel and Uchman, 2012; Nara, 2014; Soria *et al.*, 2014; Nagy *et al.*, 2016; Reolid *et al.*, 2016; Giannetti *et al.*, 2018).

As reflected by the intense bioturbation, a great amount of nutrients and phytodetritus transported by storms and waves allowed for the establishment of a densely populated benthic community. Although

Figure 3. Panoramic view (drone image) of the Cabo de la Huerta section. Image courtesy of Jaime Cuevas.



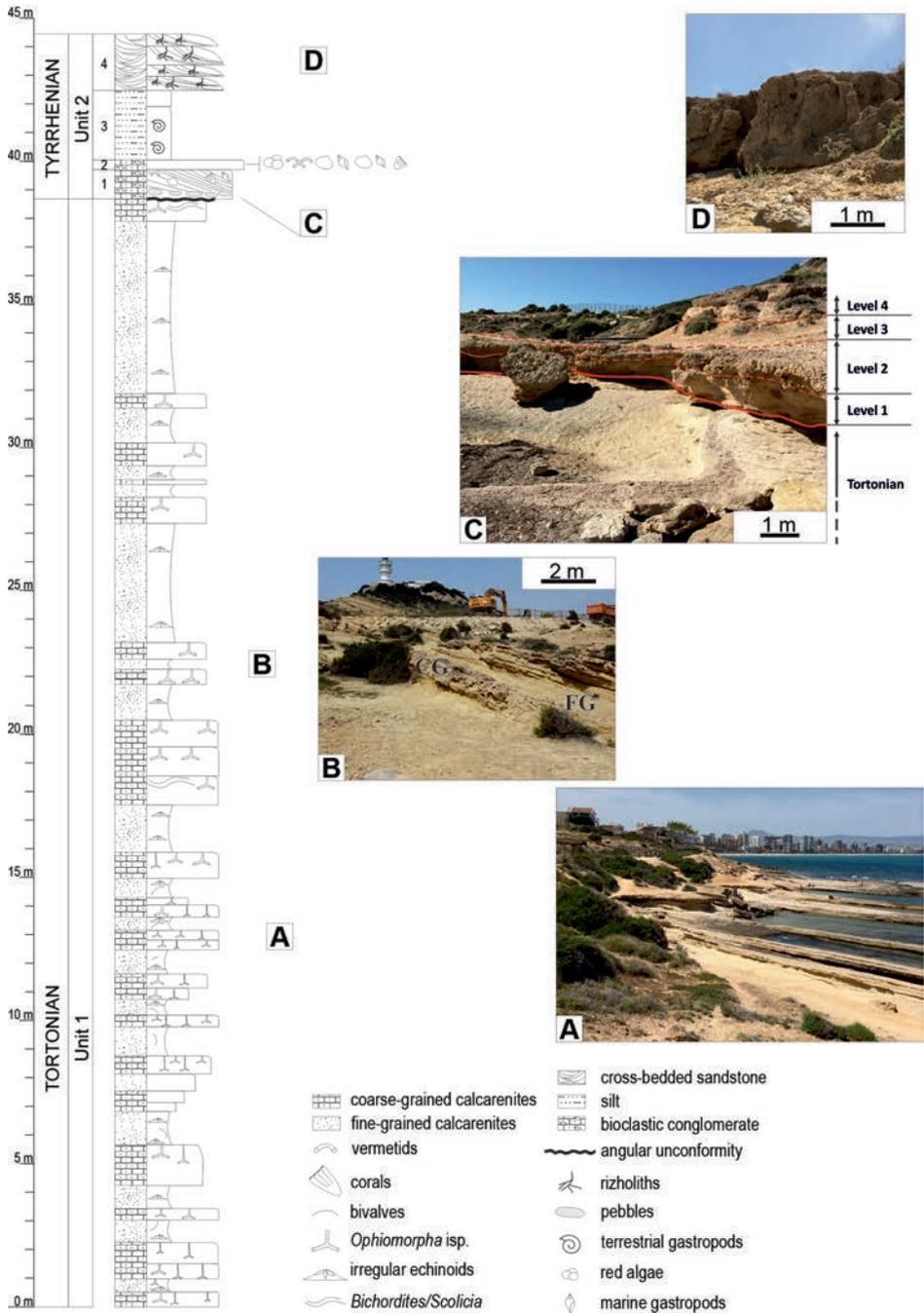
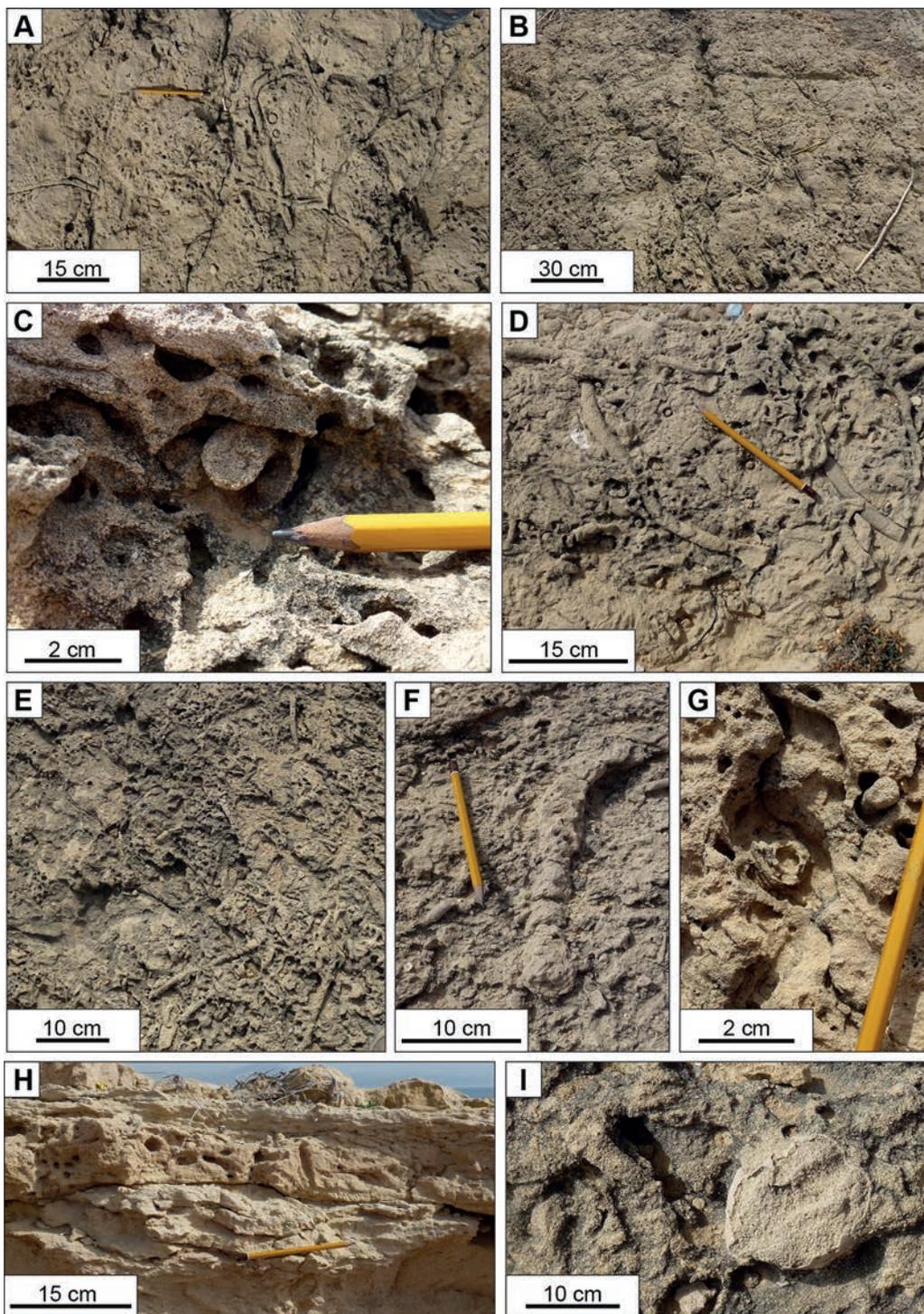


Figure 4. Stratigraphic log of the Cabo de la Huerta section. The most characteristic facies are represented and their positions marked in the log with letters. Burrow penetration depth is not to scale. CG and FG: coarse- and fine-grained calcarenites respectively. Modified from Giannetti *et al.* (2019).



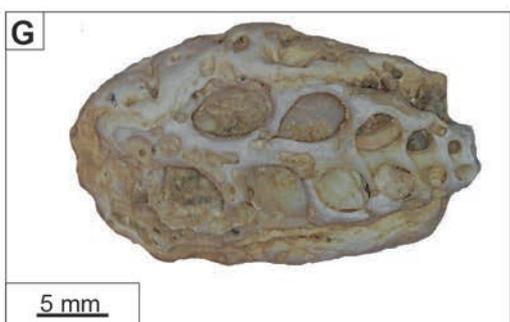
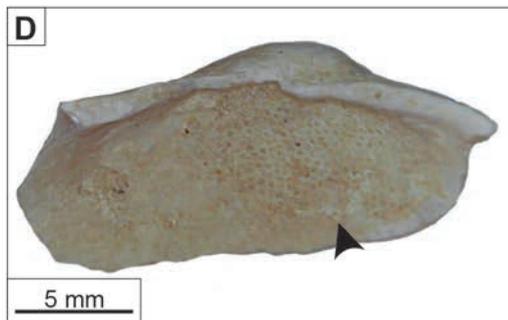
the presence of vertical shafts and complex 3D boxworks in *Ophiomorpha nodosa* suggests that the domichnia and the fodinichnia ethologic categories are represented (Nickell and Atkinson, 1995; Giannetti *et al.*, 2017), the great abundance of Y-branched horizontal tunnels reveals that the *Ophiomorpha* “trace-maker” was mainly a detritus feeder (Uchman, 2009; Rajchel and Uchman, 2012; Giannetti *et al.*, 2017). *Ophiomorpha*-producing crustaceans are considered opportunistic burrowers frequently associated with event beds, exploiting the seafloor immediately after the deposition of the food- and oxygen-rich sediments transported by storms. *Bichordites monastiriensis* and *Scolicia* isp. also indicate a detritus feeding strategy (Uchman, 1995; D’Alessandro and Uchman, 2007; de Gibert and Goldring, 2008; Buatois and Mángano, 2011; Buatois *et al.*, 2017). This suggests that quite a great amount of organic matter was present in the substrate in order to make possible the development of such a population. Intense bioturbation is surely one of the causes of the absence of clear sedimentary structures in the coarse-grained calcarenites, this preventing the exact determination of the type of currents that led to the genesis of these beds, although all the data are consistent with a storm-dominated scenario.

In contrast, in the fine-grained interbedded material burrows are extremely scarce and represented only by *Thalassinoides/Ophiomorpha* tunnels proceeding from the overlying coarse-grained calcarenites. Other types of trace fossils are absent, notwithstanding the abundance of fossil tests of irregular echinoids, which are well-known burrowers. The most important causes that can be taken into account in order to explain this apparently paradox are the burrowing mechanism of the echinoids (with only backfilling being considered as able to produce *Scolicia*- or *Bichordites*-type trace fossils), sediment texture (with well-sorted material making the preservation and visibility of the biogenic structures more difficult), firmness, and tiering (with soupy bottoms and shallow-tiered burrows representing the most difficult preservation conditions) (Kanazawa, 1992, 1995; de Gibert and Goldring, 2008). These fine-grained calcarenites would represent sedimentation during background conditions.

Taphonomic analysis gives results that are coherent with the proposed model, i.e. coarse- and fine-grained calcarenites representing event beds and background sedimentation, respectively. In fact, in the fine-grained beds, bioclasts are found with very scarce corrosion, with echinoids often in life position (Fig. 6 A, B) and showing perfect preservation. In the coarse-grained calcarenites, most of the bioclasts are very hard to recognize because of the intense fragmentation. The small size of the bioclasts suggests moreover that the shells were already highly fragmented in the source area, which implies a proximal platform with high hydrodynamic background conditions.

Through the ichnological characterization of the event beds detection of eroded storm events was possible. In fact, in the fine-grained calcarenites coarse-grained filled truncated *Ophiomorpha* can be observed apparently unrelated to coarse-grained beds. These burrows mark the position of event beds not preserved in the sedimentary record because eroded by subsequent currents. This allowed to refine the stratigraphy of the area and to detect a decrease in the frequency of event beds from the bottom to the top of the section (Fig. 4), compatible with a deepening-upward trend.

Figure 5. Bioturbation in the Tortonian material. Modified from Giannetti *et al.* (2019). A-B. High density of trace fossils at the top of tempestite beds, with branched, horizontal, and vertical *Ophiomorpha nodosa* tunnels. C. *Bichordites monastiriensis* showing internal chord and outer mantle. D-E. *Ophiomorpha* ichnoassemblage characterized by a very high density of trace fossils, top of a storm bed. F. Large echinoid burrows (*Scolicia* isp.) at the top of a tempestite bed. G. *Bichordites monastiriensis* with internal cord. H. Tempestite bed with an abrupt base completely burrowed by *Ophiomorpha* boxworks. I. Echinoid test preserved at the top of a burrowed sandy tempestite.



Tyrrhenian unit

The Tyrrhenian unit overlies the Tortonian one after an angular unconformity. The description is given following the subdivision in 4 levels (Fig. 4).

In Level 1 red algae, bivalves, gastropods (including vermetid tubes), bryozoans (*Myriapora truncata*), and corals (*Cladocora caespitosa*, *Balanophyllia* sp.) are present, although tiny fragmented. As for bivalves, a couple of valves of *Glycimeris* and a fragmented *Spondylus* were recognized, but for most of the other shell remains preservation was too poor for a reliable classification. Gastropods are represented by fragments of vermetid tubes, scarce *Patella* specimens, and other unrecognizable juveniles. Seaward-dipping laminations with wedge-shaped set boundaries, good size sorting, the sandy grain-size and absence of oscillation-related sedimentary structures suggest a foreshore. In this context, the horizons rich in aligned bioeroded pebbles and large marine bioclasts represent exceptional higher-energy events due to more intense waves.

Level 2 is characterized by larger bioclasts. The most common taxa are (in order of abundance) *Striarca lactea*, *Spondylus gaderopus*, *Chama gryphoides*, *Pseudochama gryphina*, *Barbatia barbata* and *Arca noae* among bivalves, and *Columbella rustica*, *Monodonta turbinata*, *Cerithium renovatum*, *Conus ermineus*, *Trivia mediterranea*, *Luria lurida*, *Trunculariopsis trunculus* and *Stramonita haemastoma* as for gastropods (for the complete record see Giannetti *et al.* 2019). Most of these taxa are typical of rocky substrates, although bivalves as *Glycimeris glycimeris* and *Venus verrucosa* were also recovered, which usually colonize sandy bottoms. Taxa as *Persististrombus latus*, *Luria lurida*, *Monoplex parthenopeus*, which are representative of the so-called Senegalese fauna, are also present.

Taphonomic analysis shows important differences in preservation for the same taxa (Fig. 6C-H), being completely abraded shells mixed together with shells with the fine external ornamentation and colour still preserved. This suggests a mixed association, where bioclasts with a very long residence time on the substrate are associated together with skeletal remains buried shortly after organism death or even while still alive. Extremely well-preserved shells would represent a “snapshot” of the bottoms that is the result of mass death produced by quick deposition and rapid burial (e.g. due to storms), which prevented later additions or modifications to the shell bed. The action of strong currents is consistent with the presence of large reworked fragments of vermetid bioconstructions; the coral *Cladocora* as well (from a coastal but slightly deeper environment) shows similar evidence of transport (fragmentation and not in life-position preservation). Interestingly, modern-day bioconstructions of the vermetid *Dendropoma* mainly occur in the surf zone (Antonioli *et al.*, 1999) and does not coexist with *Cladocora* banks, which always develop at greater depths (Peirano *et al.*, 2004). Their presence in the same level is another element confirming reworking by currents, transport and resedimentation. Shell borings too imply different residence times in the taphonomic active zone, since many stages of boring development coexist in the same assemblage.

Figure 6. Taphonomy of the Tortonian and Tyrrhenian skeletal remains. Modified from Giannetti *et al.* (2019). A-B. The most common preservation pattern in the echinoids of the Tortonian unit. Tests are usually partially filled by sediment and flattened. Fragmented tests are also present and associated to the unbroken ones. C. Tyrrhenian unit. Valves of *Spondylus gaderopus* from level 2. Note the different preservation, with the central valve severely affected by bioerosion and abrasion. D. Tyrrhenian unit. View of the interior of a valve of *Arca noae* from level 3. Note the bryozoans in the interior of the valve (black arrow). E. Tyrrhenian unit. *Monodonta turbinata* from level 2. In this case, the periostracum is preserved. F. Tyrrhenian unit. Vermetids from the top of level 2. Vermetids are found as fragmented and reworked centimetric blocks. G. Tyrrhenian unit. Gastropod (*Cerithium renovatum*) abraded and completely encrusted by red algae. H. Tyrrhenian unit. Three specimens of *Columbella rustica* from level 2 showing different patterns concerning preservation of colour, ornamentation, and abrasion of the apex. Preservation is better from left to right.

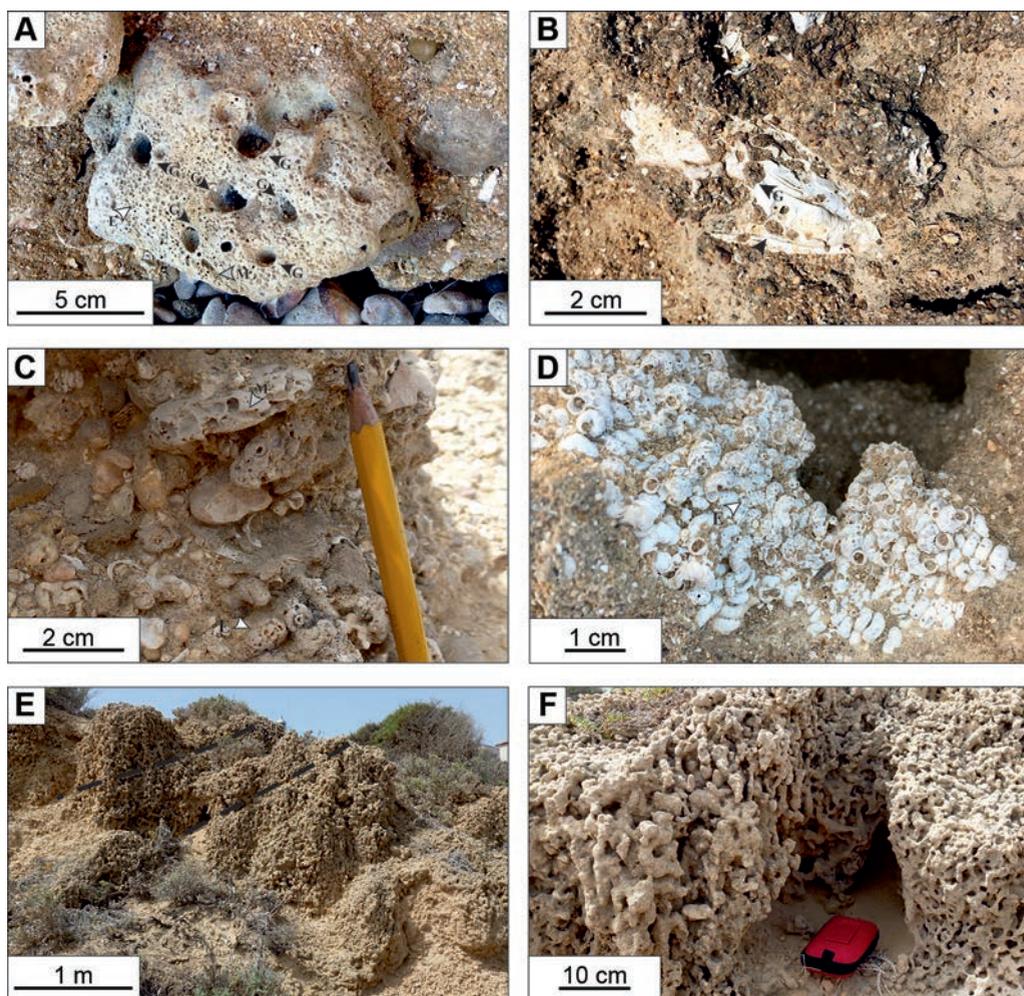


Figure 7. Bioerosion and bioturbation in the Tyrrhenian material. Modified from Giannetti *et al.* (2019). A. Bioerosion on a lithoclast in level 1: *Gastrochaenolites* isp. (G, black arrows), *Entobia* (E, white arrows), and *Maeandropolydora* (M, grey arrow). B. *Gastrochaenolites* isp. (G, arrow) on a thick-shelled bivalve. C. Bioeroded bioclasts in level 2. *Maeandropolydora* isp. (M, grey arrow) and *Entobia* isp. (E, white arrow). D. Vermetids bioeroded by *Entobia* (E, white arrow). E. Rhizoliths in the cross-bedded sandstones at the top of the section. Ghosts of lamination and bedding are still visible despite the intense bioturbation. F. Close up view of the rhizoliths.

The whole of the taphonomical, ichnological and palaeoecological data is consistent with the interpretation of level 2 as a shell bed derived from the rapid deposition of bioclasts under high-energy conditions as, for example, a particularly violent storm, which transported material from the fore- up to the backshore.

On large lithoclasts and shells, *Gastrochaenolites* and *Entobia* are recurrently found together (Fig. 7A-B), which is indicative of the development of the *Entobia* ichnofacies on rockgrounds before erosion and resedimentation of the blocks. This ichnofacies corresponds to long colonization windows in stable substrates with low sedimentation rates, particularly in rocky shore settings (Bromley and Asgaard, 1993;

de Gibert *et al.*, 2007). The same is found on vermetid blocks (Fig. 7D). On small lithoclasts, also superficial bioerosion typical of short-term exposure and mobile substrates represented is preserved (Fig. 7C)

Level 3 is a thick massive silty bed with terrestrial gastropods and sporadic fragmented benthic and planktonic foraminifer. This records the presence of a freshwater lagoon in the backshore,

Level 4 is a dune-shaped, laminated, and bioturbated sandstones from this level (Fig. 7E, F). Dunes are rich in rhizoliths, recognizable as vertical tubes with branches close to the vertical plane and thinner than the main tube; a downward decrease in tube diameter can be locally observed. Bioturbation is extremely dense from the top to the bottom of the cross-bedded bed penetrating lamination. This level records intense plant colonization of the backshore and partial stabilization of the dunes.

STOP 2: The Messinian atoll coral reef of Santa Pola

INTRODUCTION

In the stop 2 a fossil coral reef (atoll type, Messinian age, northern sector of the Bajo Segura basin) will be visited (Figs. 8 and 9). This coral reef system is located close to Alicante city, the capital city of the province. The mountain, where the geosite is included, is located less than 5 km from Santa Pola city. It comprises a calcareous platform, 5 km in diameter, isolated and elevated above the surrounding area (Corbí *et al.*, 2018). The Santa Pola Mountain is a natural promontory more than 140 m high directly in contact with the coastline and circular on a kilometric scale (north-south axis of 5 km and east-west axis of 6 km).

This atoll coral reef is one of the most relevant geosites from the Neogene record of southeastern Spain (Corbí and Yébenes, 2012; Corbí *et al.*, 2018). Its scientific and didactic value has been reported in various geosites inventories and catalogues, being the most important: 1) geosite (Spanish Geosite Inventory (LIG) carried out by the Geological and Mining Institute of Spain), and 2) palaeontological catalogue of the Community of Valencia. The site has a remarkable scientific interest with dozens of paper published

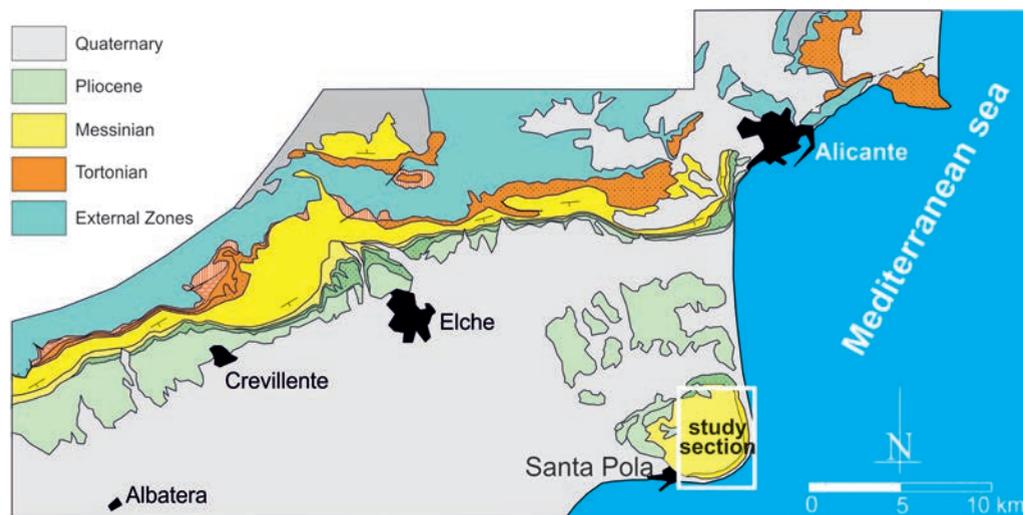


Figure 8. Synthetic geological map of the northern sector of the Bajo Segura basin, indicating the location of the study section. Modified from Corbí (2010).

in the last fifty years (Montenat, 1977, 1990; Esteban and Giner, 1977; Esteban, 1977, Esteban and Giner, 1977, Esteban *et al.*, 1978, Esteban, 1979, Esteban *et al.*, 1996, Esteban, 1997; Vallés 1985, 1986; Montenat, 1990; Calvet *et al.*, 1991, 1994, 1996; Feldmann, 1995; Feldmann and Mackenzie 1997; Soria *et al.*, 2005, 2008a, b; Corbí, 2010; Corbí and Soria, 2016; Corbí *et al.*, 2018). Moreover, this coral reef has been studied by petroleum companies that have organized specialized field trips in the area. Additionally, the site is included in the didactic guidebook *Geological Walks of the Province of Alicante* (GeoAlicante Research Team 2010). Additionally, the site is included in various chapters in books related to the geology of the southeastern Spain (Alfaro *et al.*, 2004a, 2004b; Corbí and Yébenes, 2012). The high didactic interest to promote geoheritage encouraged that the site was selected to hold the 2013 Alicante Geología public field day (Aberasturi *et al.*, 2013).

This atoll was developed during the Messinian, about 20 km southeast of the Messinian palaeocoast. Actually, the current relief allows to identify the original morphology of the atoll, with excellent outcrops where it is possible to recognize the 3D geometry of this geosedimentary structure, which is the main objective of the itinerary (Fig. 9). Recently, the implemented quantitative assessment methodologies carried out by Corbí *et al.* (2018) evidence that this exceptionally relevant scientific geosite also has a high didactic and tourism-recreational potential.

Location

Santa Pola mountain,

Coordinates: Latitude: 38°12'32.90"N Longitude: 0°31'37.56"W, Geological map of Spain, 1:50000, sheets of Elche (893) and Cabo de Santa Pola (894).

Geological setting: Bajo Segura basin.

Main topic: sedimentary environments and the fossil record in coral reef.

Aims

Show the outreach activities developed for the promotion of the Geoheritage of the site.

Identify and characterize the representative sedimentary environments of a coral reef.

Recognize the main coral facies of the site.

Description

Geological and sedimentary context

Geologically, the Santa Pola Messinian coral reef is located in the northern Bajo Segura basin, a western Mediterranean Neogene basin of the eastern Betic Cordillera (Fig. 8). The general stratigraphic architecture is based on Corbí *et al.* (2018), Calvet *et al.* (1996), Esteban *et al.* (1996) and Feldmann and Mackenzie (1997). Our own field observations allow to differentiate (in stratigraphical order) the following units: (a) Tortonian yellowish calcarenites with rhodoliths equivalent to the Tabarca Unit (see Martínez-Martínez *et al.*, 2017); (b) the reef complex, the Messinian atoll coral reef, the focus of the present paper; (c) the terminal carbonate complex (TCC of Esteban, 1979), an upper-Messinian marine unit characterized by predominantly stromatolite (mainly dome shaped) and oolite facies (recently studied by Villafañe *et al.* (2018)); (d) Pliocene marine marls and fossiliferous sandy limestones related to the Pliocene reflooding of the Mediterranean (Corbí and Soria, 2016); (e) upper Pliocene–Pleistocene continental red claystones and limestones (Sucina Formation of Montenat, 1990); (f) the pre-Tyrrhenian marine terrace



Figure 9. Panoramic views (the central a drone image) of the coral reef complex where is possible to recognize the main sedimentary environments: lagoon, reef front, slope and *Halimeda* fan. In the upper image the reef wall in the foreground and the Alicante coastline in the background.

(middle Pleistocene), which occurs above an abrasion surface carved in materials of the marine reef slope from the reef complex (Goy and Zazo, 1988); (g) breccias of the subaerial slope, a deposit of the continental bottom ledge formed by fragments of the exhumed reef front; and (h) Tyrrhenian marine terraces (upper Pleistocene) carved in the distal sectors of the colluvial border, where three levels of marine beaches and eolian dunes can be differentiated (Goy and Zazo, 1988).

Sedimentary facies recorded

The examining of the current relief shows the original morphology of the atoll, providing excellent outcrops where the three-dimensional geometry of the different parts of the coral reef can be recognized (Figs. 9, 10 and 11). In the reef complex, three sedimentary environments can be identified:

a) The reef front (semi-circular ledge defining Santa Pola mountain). Notable regularly spaced channels as well as regularly distributed buttresses along the entire reef crest can be recognized; it is almost exclusively dominated by *Porites* genera (Fig. 10A), which assemblages show clear morphological zoning distinguishable in the reef wall (from lower to upper): (a) dishes or plate-like zone; (b) branching zone of finger-like morphologies more or less branched, constituting the main section of reef wall; and (c) a massive coral zone, cropping out in the upper part of the reef crest. It is also significant that fan-shaped *Halimeda* packstones and grainstones and yellowish calcarenites developed in front of the channels (Fig. 9 and 10B).

b) The reef slope. It is developed from the reef front to the ancient open platform; it coincides with the current slope, and thus the deposits are partially covered by rocks fallen in more recent times in subaerial conditions.

c) Lagoon or back reef zone. It is formed mostly by reef patches and calcarenites with *Halimeda* and bivalves. This coral reef facies were mostly eroded before sedimentation of the newest, Pliocene–Pleistocene materials, which comprise the upper part of Santa Pola mountain.

It should be noted that a large number of fallen blocks (of metric scale) can be observed near the Marine Research Centre of Santa Pola (CIMAR, Santa Pola municipality, University of Alicante), where the coral reef facies characterization will be performed in the stop 2 of the itinerary (Fig. Fig 9 and 10). This are is the ideal didactic and outreach site to recognize different *Porites* coral assemblages. Indeed, one of these blocks is included in the rock garden of the University of Alicante, a didactic space inside the university, where a selection of the different rock types from the Betic Cordillera and Bajo Segura basin are exhibited.

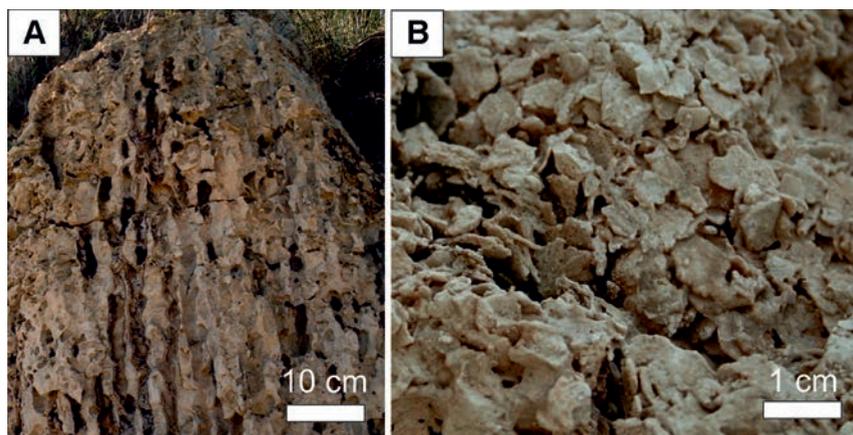


Figure 10. Representative fossils of the coral reef: A: Branch-like morphologies of *Porites* in the reef wall; B: Detailed image of the *Halimeda* packstones.

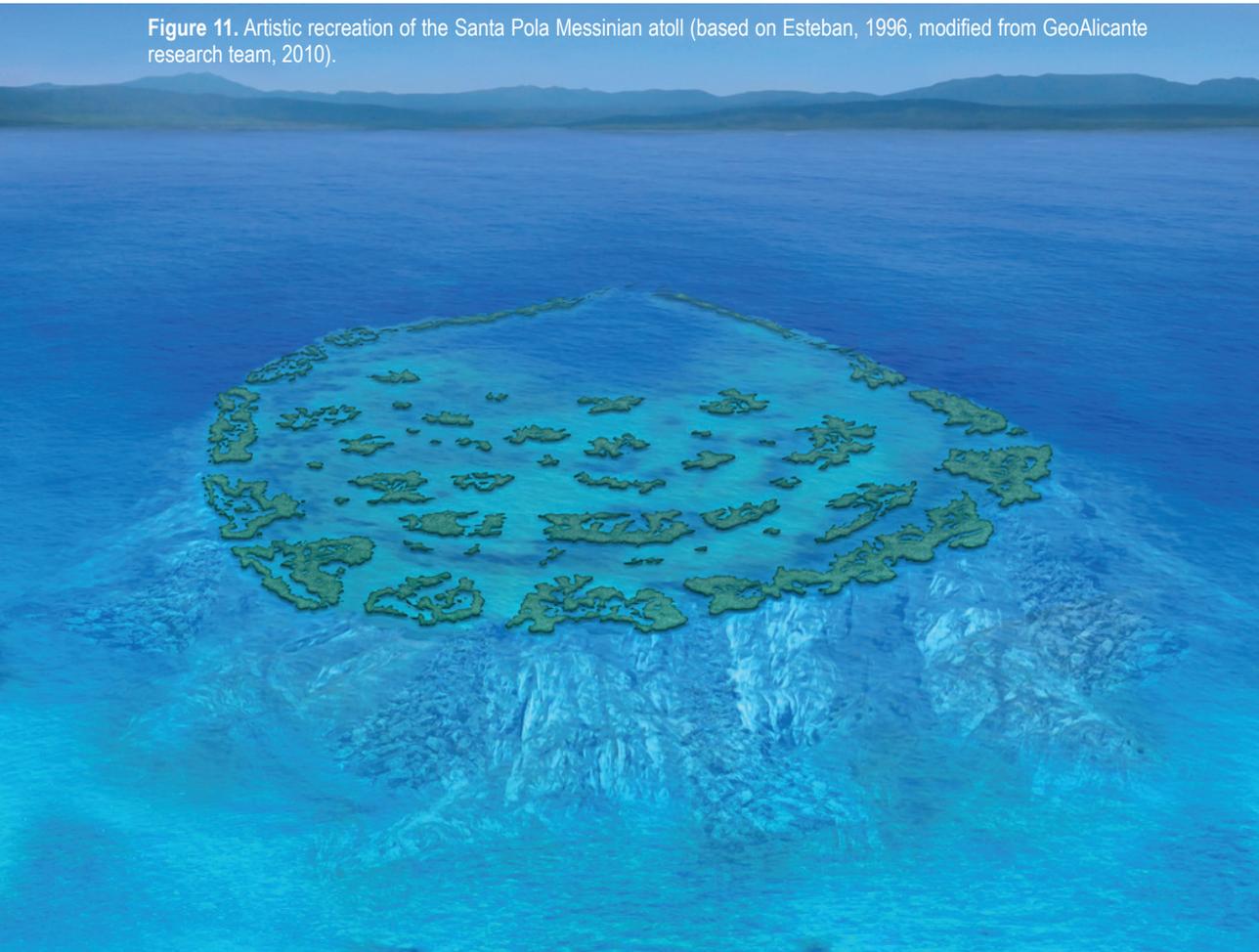
3D Geosedimentary models to promote the paleontological heritage

In this itinerary we present different 3D scale scale Geomodels of this relevant Messinian site, which can be an essential key not only to teach geoscience at different educational levels, but also to promote an disseminate to general public the geoscientific and didactic value of these distinctive sedimentary environments (Figs. 12 and 13).

The 3D scale Geomodels (20 x 20 cm each one) has been developed at two different scales: the entire atoll structure and the best representative outcrop, which has been identified combining the analysis of the digital elevation model (hydrography network) and directly observational field data (Fig. 12A). In this outcrop a high-resolution 3D model (Fig. 12B) has been developed with the Structure from Motion photogrammetric technique processing about 1000 high-resolution images carried out with Remotely Piloted Aircraft Systems (Drone Phantom DJI 3 Advanced).

Two different 3D models have been implemented for each selected scale (4 models in total, 20 x 20 cm): the first, reproducing the current relief (small mountain above the sea level); and the second, an artistically and geoscientific recreation attempting to simulate the sedimentary environments during the Messinian formation process (Fig. 13). The process of geomodelization includes the following steps: a) print the models with a 3D printer Vulcanus Max 40, FDM, PLA material; b) generation of plaster molds and silicone counter molds; c) remove and polish de Pliocene and Quaternary erosion adding plaster in the canyons and gullies; d) generation (remodeling manually with plaster the textures and reliefs) of the geomorphic features, actually eroded or buried under more recent sediments (principally patch reefs, and back-reef

Figure 11. Artistic recreation of the Santa Pola Messinian atoll (based on Esteban, 1996, modified from GeoAlicante research team, 2010).



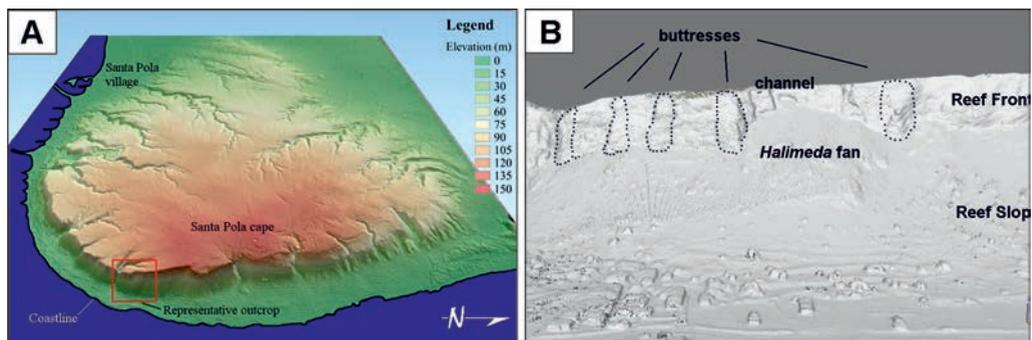


Figure 12. A. Digital Elevation Model of the Santa Pola Coral reef. B. High resolution 3D model of the representative outcrop (Structure From motion technique). Figure courtesy of Francisco Asensio-Montesinos.

zone; see Fig. 13); e) coloring the scale models emulating similar sedimentary environments represented (original geomorphic structures); f) covering (without pasted) the 3D model with blue epoxy resin in order to simulate the marine environment; and g) elaboration of an infographic transparent sheet signaling the different sedimentary parts of the coral reef (front view) and the geological cross section (lateral view).

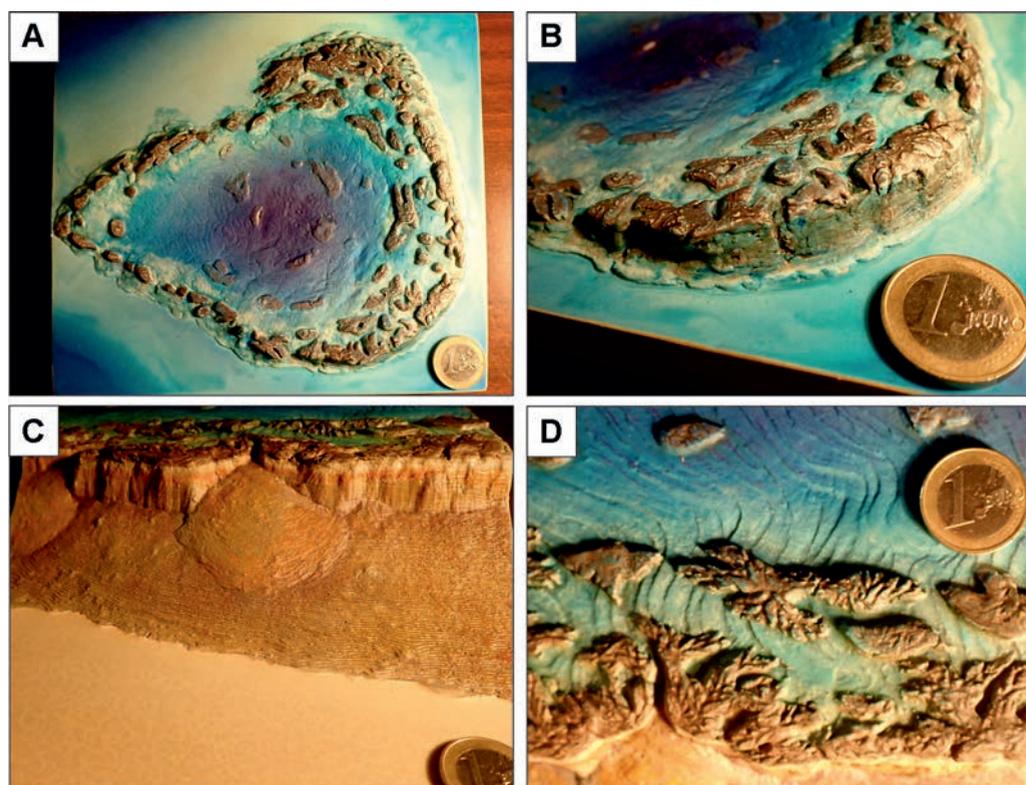


Figure 13. A. 3D scale geosedimentary models of the Santa Pola Coral reef (A-B: entire coral reef structure -atoll type-; C-D: best representative outcrop, where the stop 2 will be performed). In all images coin for scale.

STOP 3: Paleontological Museum of Elche (MUPE): The Miocene Collection

Location

The Paleontological Museum of Elche (MUPE, its initials in Spanish) is located in the city of Elche, in the district of Baix Vinalopó, Alicante, Spain.

Aims

To look at the movable heritage linked to the MUPE, focusing on the collections of this part of the Betic Range and more specifically on all the remains related to the Bajo Segura Basin.

Description

In 1982, three years before the Spanish Act 16/1985, on Spanish Historical Heritage, a group of paleontology enthusiasts with a common drive and interests decided to create the Paleontological Cultural Group of Elche (GCPE, its initials in Spanish). Unbeknownst to them at the time, they were taking the first step to form what years later would be the MUPE.

The GCPE was a meeting point for paleontology enthusiasts in Elche and the surrounding areas. After the creation of a board of directors, members sought contact with the City Council of Elche to achieve

Figure 14. The Palaeontological Museum of Elche receives about 20.000 visits along the year.





Figure 15. FOPALI Project is the tool of the museum for palaeontological heritage management. For example, it has been used at different locations in the province of Alicante and Murcia (Spain) and in Niger (Africa). Excavation of *Spinophorosaurus nigerensis*.

the objectives initially set: unite the collections and have a space to house them and make them known to the general public. Over time, new members joined the group and contacts were established with different Spanish universities and museums around the world. At that time, our publication, the *Journal of Paleontology and Mineralogy Cidaris* (of which 32 issues have now been edited) also launched. The paleontological heritage of Elche was beginning to be known and the destruction of paleontological outcrops was also noted, aspects that were already denounced.

In 1996, the collection was declared to be a Museographic Collection of Paleontology and incorporated into the Network of Museums of the Community of Valencia. From this moment on, outreach activities began to be organized.

Society's growing interest in learning about paleontological heritage and the work of the GCPE led to the City Council of Elche's converting a space to be the Paleontological Museum of Elche, which opened on December 3 of 2004. Currently, the museum is managed by the Cidaris Foundation and has partnered with geologists and biologists who work on specific projects.

Since then, the museum has become a benchmark in Alicante as it is the only paleontology museum in the entire province that supports research projects related to heritage (e.g. Fierro, 2015; Sánchez-Ferris, 2016) and conservation and didactic projects of geological and paleontological heritage (e.g. Aberasturi *et al.*, 2014), three basic pillars on which every museum is based.

Since 2007, an ambitious project has been carried out for dissemination, outreach, and didactic purposes — the didacPAL Project. This project covers a variety of activities ranging from paleontological



Figure 16. View of part of the Messinian collection from MUPE.

guided tours to workshops, and the publishing of academic support materials specifically designed for different educational levels, as well as activities for the general and specialized public (Fig. 14).

Paleontological and geological heritage preservation has always been a priority for the MUPE and Cidarís Foundation. Consequently, a work strategy in which heritage assessment is conceived as a management tool has been developed — FOPALI (Fig. 15).

The work plan of the FOPALI Project takes as its starting point the existence of a geological and paleontological heritage that is recorded in the form of an inventory. The next step is the heritage assessment of the points included in the inventory. To do so, a set of criteria is used that allows the ordering of heritage assets according to their importance. Finally, social projection should not be forgotten as one of the most important purposes of this project, which implies the development of management proposals and enhancement of inventoried and valued locations.

The museum collections include fossils, minerals, and recent shells. The upper floor focuses on the province's geological heritage, introducing visitors to the most important paleontological sites from the Triassic to the Quaternary.

The permanent Miocene collection is represented by marine and continental fossils, documenting the diversity and the species that habited the surrounding areas during this epoch. Fossil invertebrates like bivalves, gastropods, equinoids, and corals illustrate the marine ecosystems (Figs. 16 and 17).

Vertebrates are well represented by fossils from a paleontological site named Crevillente 2 (CR2, Crevillent, Alicante). CR2 is undoubtedly one of the most interesting sites with mammals in the province of Alicante, with 40 species identified, including *Hipparion*, saber-toothed tigers, a short-necked giraffe, a deer, a skunk, a hyena, crocodiles, turtles, and two proboscians.



Figure 17. View of the Miocene echinoderm collection from MUPE.

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