Journal of Iberian Geology
https://doi.org/10.1007/s41513-025-00295-9

RESEARCH PAPER

Zonal scales of brachiopods, foraminifera, ostracods and palynomorphs from the Lower/Middle Jurassic transition in the Iberian Peninsula: calibration with ammonoid zones

Soledad Ureta[1] · Gemma Martínez[1] · Benito Andrade[2] · Carmen Arias[1] · Eduardo Barrón[3] · María Luisa Canales[1] · Alejandra García-Frank[1] · Fernando García Joral[1] · Maria Helena Paiva Henriques[4] · José Sandoval[5]

Received: 26 February 2025 / Accepted: 8 May 2025

Abstract

The aim of this work was to synthesize all the data obtained over the last four decades by the various researchers who have formed part of the multidisciplinary Jurassic research group founded by Professor Antonio Goy. This is, therefore, a review that seeks to integrate data from various studies on different fossil groups in the Iberian Peninsula during the transition from the Early to the Middle Jurassic. The boundary between the Early Jurassic and Middle Jurassic in the Iberian Peninsula is represented by alternating calcareous and marly levels containing abundant fossils of benthic, planktonic, and palynomorphic organisms. Among all of these, the ammonoids offer the best high-resolution biostratigraphy. A detailed review of the ammonoids zonal scales established in the Iberian Peninsula (Iberian Cordillera, Betic Cordillera, Basque-Cantabrian Basin and Lusitanian Basin) has been carried out. Besides, the ammonoid scales defined in the different areas of the Iberian Peninsula have been compared with the standard zonation for northwestern Europe and with the Mediterranean zonation based on the hammatoceratid group, defined in the Betic Cordillera. All these ammonoid scales have been calibrated with established regional scales using brachiopods, foraminifera, ostracods, palynomorphs, and biofacies samples to highlight which species are useful for establishing correlations within the Iberian Cordillera and with other basins in the western Thetys.

Keywords Cronostratigraphy · Biostratigraphy · Toarcian–Aalenian boundary · Ammonoids · Correlations

---

✉ Gemma Martínez
gemmamar@ucm.es

Soledad Ureta
solureta@ucm.es

Benito Andrade
benitoandradeg@gmail.com

Carmen Arias
carias@ucm.es

Eduardo Barrón
e.barron@igme.es

María Luisa Canales
mcanales@ucm.es

Alejandra García-Frank
agfrank@ucm.es

Fernando García Joral
fgjoral@ucm.es

Maria Helena Paiva Henriques
hhenriq@dct.uc.pt

José Sandoval
sandoval@ugr.es

[1] Departamento de Geodinámica, Estratigrafía y Paleontología, Universidad Complutense de Madrid, C/ José Antonio Nováis, 12, 28040 Madrid, Spain

[2] MARE (Marine and Environmental Sciences Centre), 3030-790 Coimbra, Portugal

[3] Museo Geominero, Instituto Geológico y Minero de España (IGME-CSIC), Ríos Rosas 23, 28003 Madrid, Spain

[4] Centro de Geociências y Departamento de Ciências da Terra, Faculdade de Ciência e Tecnologia de Coimbra (Polo II), Rua Sílvio Lima, 3030-790 Coimbra, Portugal

[5] Departamento de Estratigrafía y Paleontología, Universidad de Granada, Av. Fuentenueva s/n, 18002 Granada, Spain

Escalas zonales de braquiópodos, foraminíferos, ostrácodos y palinomorfos de la transición Jurásico Inferior/Jurásico Medio en la Península Ibérica: calibración con las zonas de ammonoideos

Resumen

Este trabajo se ha realizado con el propósito de establecer una síntesis de todos los datos obtenidos a lo largo de las últimas 4 décadas por parte de los diferentes investigadores que hemos formado parte del grupo de investigación multidisciplinar del Jurásico creado por el profesor Antonio Goy. Este es un estudio de integración de datos de las diferentes publicaciones realizadas sobre distintos grupos fósiles estudiados en la Península Ibérica durante el tránsito Jurásico Inferior-Medio. El límite entre Jurásico Inferior y Jurásico Medio está representado en la Península Ibérica por alternancia calcáreo-margosas que contienen abundantes fósiles de organismos bentónicos, planctónicos y palinomorfos. Entre ellos es el grupo de los ammonoideos el que permite establecer una mejor bioestratigrafía de alta resolución. Se ha realizado la revisión de las escalas zonales de ammonoideos establecidas en la Península Ibérica (Cordillera Ibérica, Cordillera Bética, Cuenca Vasco-Cantábrica y Cuenca Lusitánica). Se han comparado las escalas de ammonoideos definidas en las diferentes áreas de la Penísula Ibérica con la zonación estándar del NW de Europa y así mismo se ha comparado con la zonación mediterránea basada en el grupo de los hammatocerátidos, definida en la Cordillera Bética. Se ha efectuado la calibración de todas estas escalas de ammonoideos con las escalas regionales establecidas con braquópodos, foraminíferos, ostrácodos, palinomorfos y muestras de biofacies a fin de remarcar cuales son las especies útiles para establecer correlaciones dentro del ámbito ibérico así como con otras cuencas del Thetys occidental.

Palabras clave Cronoestratigrafía · Bioestratigrafía · límite Toarciense–Aaleniense · Ammonoideos · Correlaciones

1 Introduction

The Toarcian–Aalenian transition (Aalensis Zone–Opalinum Zone) is well represented in many localities of the Iberian Peninsula by calcareous-marly succesions with abundant fossils of benthic and nektonic organisms and palynomorphs. Particularly, the ammonoid successions have allowed to establish a high-resolution biostratigraphic scale based on the study of the most representative stratigraphic sections in the Iberian (Fuentelsaz), the Betic cordilleras (Sierra de Ricote and Cerro Méndez) and the Lusitanian Basin (São Gião) (Sandoval et al., 2001). This paper provides new data obtained from the Basque–Cantabrian Basin (Figs. 1, 2) and presents the correlation of the zonal scales based on the record of brachiopods, foraminifera, ostracods and palynomorphs. The calibration between unit boundaries is made according to the ammonoids zonal scales established in the different basins of the Iberian Peninsula (Figs. 3, 4)).

In this paper we use the Bifidatum Subzone Contini, 1969, for the upper part of the Lower Aalenian (Opalinum Zone), replacing the "Comptum Subzone" that we have previously used (Henriques, 1992; Linares & Sandoval, 1993; Ureta, 1985). The reason for this substitution is due to the disappearance of the original material of *Nautilus comptus* Reinecke, 1818, which has been recently found and identified as *Pleydellia* from the upper Toarcian (see Chandler & Callomon, 2009; Dietze et. al., 2021). Consequently, this Toarcian species cannot be used as index for an Aalenian Subzone. The Bifidatum Subzone, more or less equivalent to the former Comptum, has been used by various authors since 1969.

The data from the Iberian Cordillera and the Basque-Cantabrian Basin are the result of several years of work carried out by a multidisciplinary team led by Professor Antonio Goy to whom we would like to express our deep gratitude and affection for the dedication he has shown to us during all these years as a teacher and friend.

2 Materials and methods

The number of specimens studied in this work is highly complex to calculate, as it involves data obtained by various specialists over the past four decades. They are found in the following repositories: Department of Geodynamic, Stratigraphy and Paleontology, Complutense University of Madrid (ammonoids, brachiopods, foraminifera, ostracods and microfacies samples from the Iberian Cordillera and the Basque-Cantabrian Basin), Department of Stratigraphy and Paleontology, University of Granada (ammonoids and foraminifera from the Betic Range), Department of Earth Sciences, University of Coimbra (ammonoids, brachiopods and foraminifera from the Lusitanian Basin), Instituto Geológico y Minero de España (palynomorphs from the Iberian Cordillera).

The fossil groups were sampled layer by layer from the different sections studied, followed by standard procedures regarding labeling, processing, cleaning and classification. For both ammonoids and brachiopods, cleaning was carried

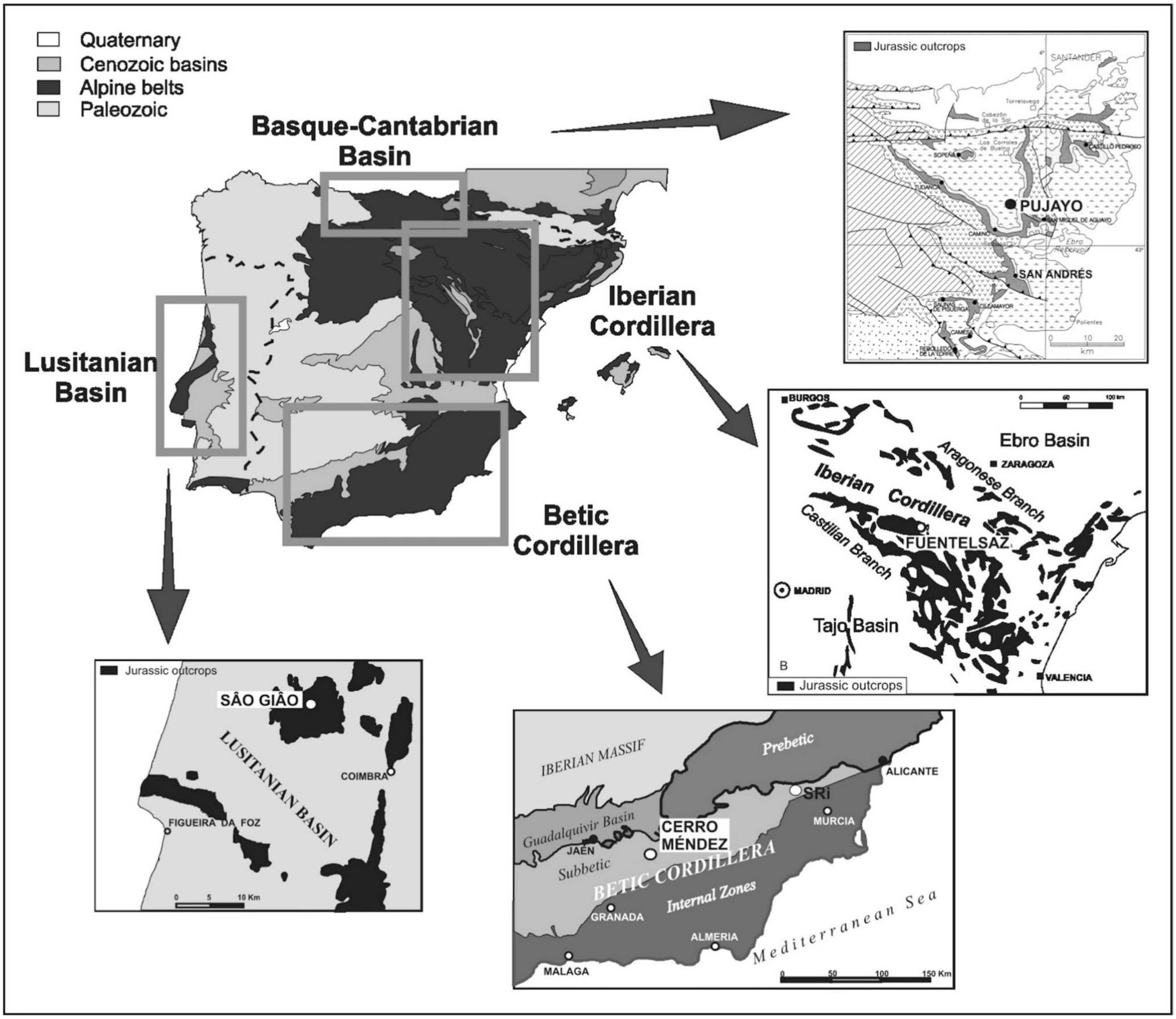


Fig. 1 Location of the studied basins in the Iberian Peninsula with the reference sections in each of them: SG, São Gião (Lusitanian Basin); CM, Cerro Méndez, SRI, Sierra de Ricote (Betic Cordillera); FZ, Fuentelsaz (Iberian Cordillera); Pujayo and San Andrés (Basque–Cantabrian Basin)

out using a percussion needle. For some brachiopods, serial oriented sections were made to obtain acetate replicas (peels) of each cut surface to reveal the internal skeleton.

For the study of foraminifera and ostracods, marl samples were recovered from outcrops, considering the thickness of the biozones and subzones, as well as the lithological characteristics of the exposed levels. Each sample, consisting of 300 g of marl, was treated in the laboratory with a mixture of water, hydrogen peroxide, and sodium hydroxide, following a standard methodology for obtaining microfossils.

Palynological samples were prepared using the standard palynological technique (Traverse, 2007), based on acid treatment with HCl and HF at high temperature. Residues were sieved through 250, 75, and 10 µm grids. After that, the slides were mounted in glycerin gel. Sixty-nine samples from 102 sediment samples collected during fieldwork conducted in the 1990s were found to contain palynological content and were examined using wide-field transmitted light microscopy.

This study includes a detailed petrographic description of the different microfacies from the Aalenian GSSP of Fuentelsaz. Polished thin sections were made of 120 samples from the Toarcian–Aalenian boundary at the Fuentelsaz GSSP and studied by transmitted-light microscopy.

Fig. 2 Panoramic views (**a, c**) and field views (**b, d**) of the referenced sections in a) Iberian Cordillera (Fuentelsaz); b) Basque-Cantabrian Basin (Pujayo); c) Lusitanian Basin (São Gião); d) Betic Cordillera (Cerro Méndez). Scale bar: 40 cm

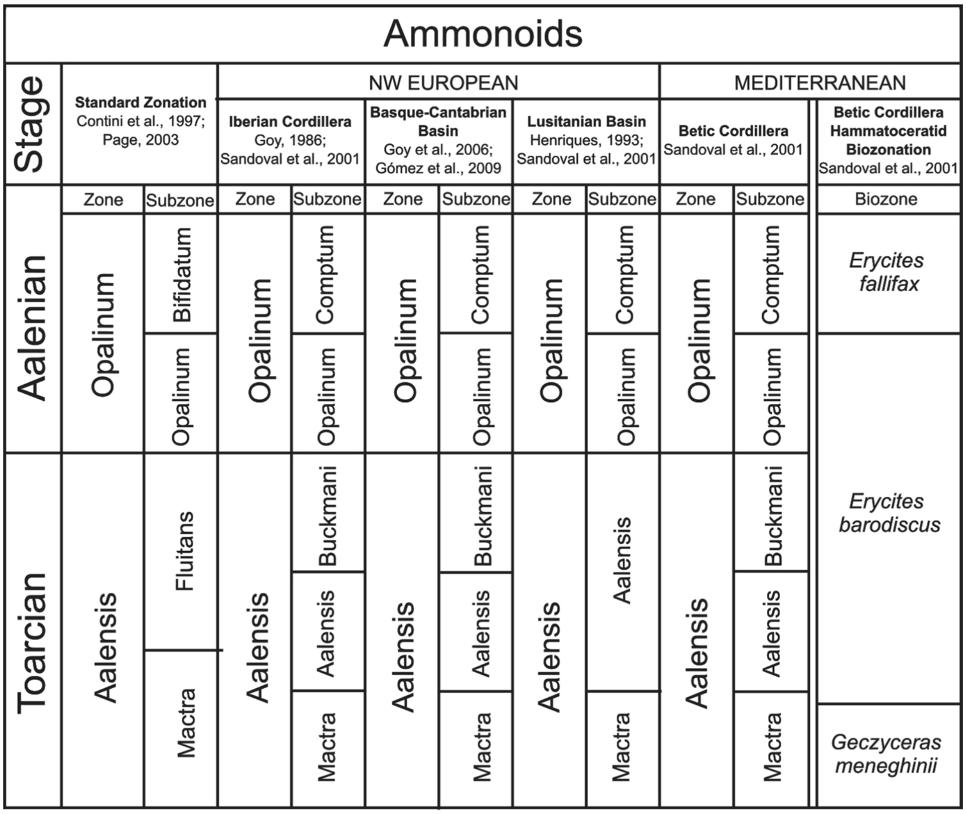
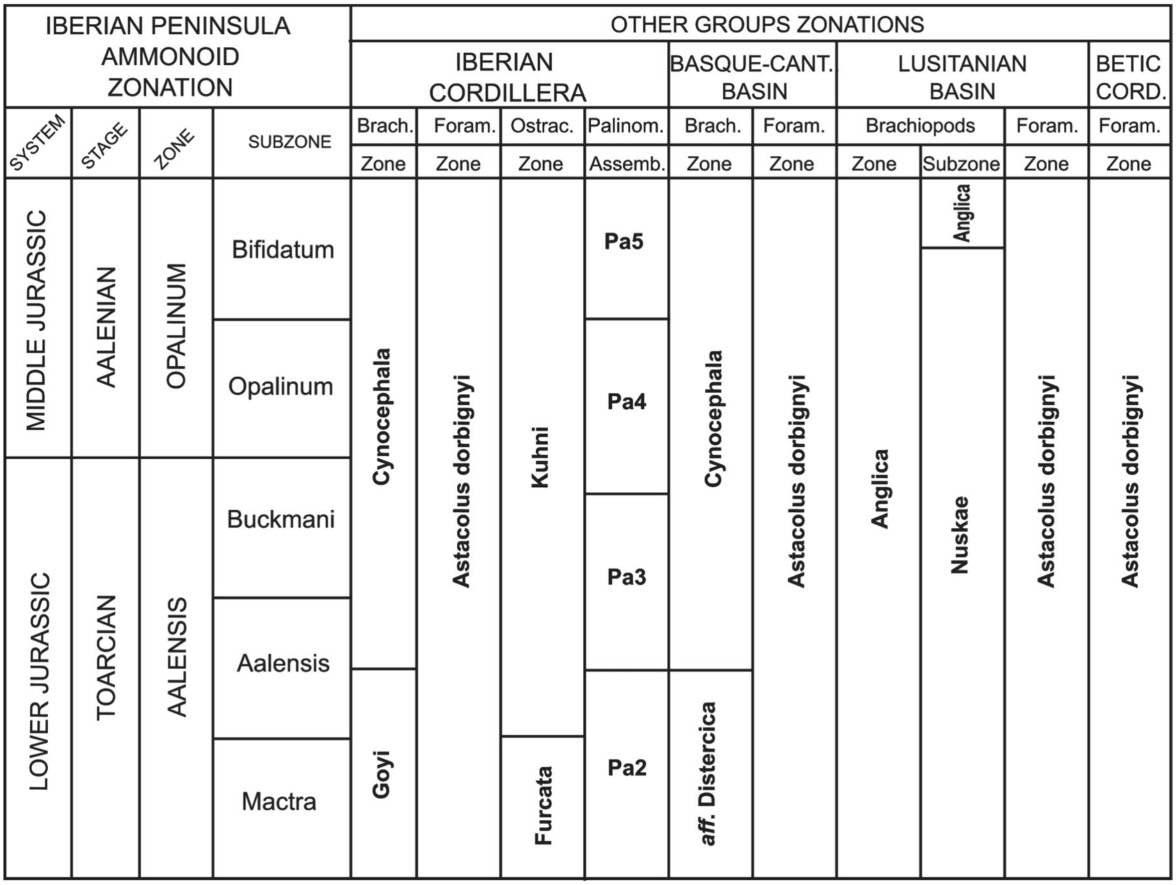


Fig. 3 Correlation between the zonal scales of ammonoids established in the different basins of the Iberian Peninsula with the Standard Zonal Scale

Ammonoids											
Stage	**Standard Zonation** Contini et al., 1997; Page, 2003		NW EUROPEAN						MEDITERRANEAN		
			Iberian Cordillera Goy, 1986; Sandoval et al., 2001		**Basque-Cantabrian Basin** Goy et al., 2006; Gómez et al., 2009		**Lusitanian Basin** Henriques, 1993; Sandoval et al., 2001		**Betic Cordillera** Sandoval et al., 2001		**Betic Cordillera Hammatoceratid Biozonation** Sandoval et al., 2001
	Zone	Subzone	Zone	Subzone	Zone	Subzone	Zone	Subzone	Zone	Subzone	Biozone
Aalenian	Opalinum	Bifidatum	Opalinum	Comptum	Opalinum	Comptum	Opalinum	Comptum	Opalinum	Comptum	*Erycites fallifax*
		Opalinum		Opalinum		Opalinum		Opalinum		Opalinum	*Erycites barodiscus*
Toarcian	Aalensis	Fluitans	Aalensis	Buckmani	Aalensis	Buckmani	Aalensis	Aalensis	Aalensis	Buckmani	
				Aalensis		Aalensis				Aalensis	
		Mactra		Mactra		Mactra		Mactra		Mactra	*Geczyceras meneghinii*



IBERIAN PENINSULA AMMONOID ZONATION				OTHER GROUPS ZONATIONS									
				IBERIAN CORDILLERA				BASQUE-CANT. BASIN		LUSITANIAN BASIN			BETIC CORD.
SYSTEM	STAGE	ZONE	SUBZONE	Brach.	Foram.	Ostrac.	Palinom.	Brach.	Foram.	Brachiopods		Foram.	Foram.
				Zone	Zone	Zone	Assemb.	Zone	Zone	Zone	Subzone	Zone	Zone
MIDDLE JURASSIC	AALENIAN	OPALINUM	Bifidatum	Cynocephala	Astacolus dorbignyi	Kuhni	Pa5	Cynocephala	Astacolus dorbignyi	Anglica	Anglica Nuskae	Astacolus dorbignyi	Astacolus dorbignyi
			Opalinum				Pa4						
LOWER JURASSIC	TOARCIAN	AALENSIS	Buckmani				Pa3						
			Aalensis	Goyi			Pa2	*aff.* Distercica					
			Mactra			Furcata							

Fig. 4 Calibration of the brachiopod, foraminiferal, ostracod and palynomorph scales established in the different Peri-Iberian basins with the Ammonoid Zonal Scale proposed for the Iberian Peninsula

3 Stratigraphy

Biostratigraphic studies in the Lower Middle Jurassic transition have been intensified in the Iberian Peninsula since the 1980s. This work has allowed the establishment of detailed biostratigraphic scales, based on ammonoids, brachiopods, foraminifera, ostracods and palynomorphs (Andrade, 2006; Barrón et al., 2010; Canales, 2001; Canales & Henriques, 2008; Canales et al., 2014; Correia et al., 2019; Cresta et al., 2001; Figueiredo et al., 2014; García Joral & Goy, 2010; Goy et al., 1984; Henriques & Canales, 2013; Henriques et al., 2016; Sandoval et al., 2001). These scales have served to refine and complete the existing biostratigraphic framework and have allowed a precise correlation between the different basins that bounded the Iberian Plate during the Mesozoic.

3.1 Iberian Cordillera

In the Iberian Cordillera, the deposits of the Toarcian-Aalenian transition present very variable thikness, whith the higest values recorded in the Castilian Branche of this peri-Iberian paleomargin. The most significant section is found at Fuentelsaz, GSSP of the Aalenian stage, where more than 35 m thick have been measured (along the Mactra, Aalensis, Buckmani, Opalinum and Bifidatum subzones). These sediments consist of an alternation of limestone and marly beds forming part of the Turmiel Fm. (Goy et al., 1976), followed upwards by nodular limestone beds of the Casinos Fm. (Gómez & Fernández-López, 2004; Gómez et al., 2003). These alternations are arranged in shallowing upward sequences, interrupted by deepening pulses where the marly fraction is dominant (Fuentelsaz, Bifidatum Subzone).

The analysis of more than 120 thin sections of samples from the Toarcian-Aalenian boundary at the Fuentelsaz GSSP allows the recognition of five main groups of microfacies: MF1. Bioclastic wackestone-packstone limestone. It occurs in the lower part of the section (Pseudoradiosa, Mactra, Aalensis subzones and the basal part of the Buckmani Subzone). Peloidal limestone with large fossil fragments, whose matrix is affected by recrystallization. The dominant fossils are thin-shelled bivalves (*Bositra*), foraminifera, brachiopods, echinoderm plates, ostracods, serpulids and gastropods, with less than 5% of vertebrate remains (fish scales) and quartz grains. MF2. Bioturbated wackestone limestone. It occurs in the Toarcian-Aalenian transition (Buckmani, Opalinum subzones and the base of the Bifidatum Subzone). They are bioclastic limestone dominated by *Bositra* filaments and frequent bioturbation structures (*Zoophycos* and *Chondrites*). In addition to thin-shelled bivalves, foraminifera, echinoderm plates, sponges (spicules), together with minor quantities of gastropods, serpulids, vertebrate remains (fish scales), ostracods, brachiopods, bryozoans and quartz grains are abundant. MF3. Bioclastic wackestone-packstone limestone. It constitutes the middle-upper part of the section (Bifidatum Subzone) consinting of limestone with abundant and diverse fossil fragments. The dominant groups are sponge spicules and gastropods (the latter predominate in the lower part). Other abundant fossils are bivalves (*Bositra*), sponges (spicules), echinoderm plates, serpulids, foraminifera and brachiopods, while minor components include ostracods, bryozoans, vertebrate remains (fish scales) and quartz grains. MF4. Mudstone limestone. It constitutes the upper-middle part of the section (Bifidatum Subzone). Dark matrix limestone with small bioturbation structures, partially affected by recrystallization processes. Its main fossils include bivalves (*Bositra*), sponges (spicules), echinoderm plates, brachiopods, foraminifera and serpulids, being ostracods, indeterminate fossil fragments and quartz grains. MF5. Bioturbated mudstone-wackestone limestone. It occurs in the upper part of the section (Bifidatum Subzone). It is a scarcely bioclastic limestone with sponge spicules. The matrix is affected by recrystallisation processes. The dominant fossils include sponges (spicules) and bivalves (*Bositra*) and in decreasing order foraminifera, echinoderm plates, ostracods, brachiopods, serpulids, vertebrate remains (fish scales very rare) and quartz grains. The microfacies fossil content includes abundant bivalves (*Bositra* filaments) throughout the section and a noticeable progressive increase of sponge spicules (from 7.7% to 51.3%) within the Toarcian-Aalenian transition upwards (García-Frank et al., 2010). In the lower portion *Bositra* filaments, foraminifera tests and echinoderms plates dominate together with the scattered and rare co-occurrence of gastropods and bryozoans. The upper portion of the section is characterized by the dominance of sponge spicules and *Bositra* filaments with abstentions of gastropods and bryozoans. Microfacies analysis show that some groups such ostracods, serpulids and brachiopods are always present with a low percentage, though in the lower part of the section they are more abundant. Diversity and evenness are useful tools for evaluating the abundance changes of the allochems within the different microfacies throughout the section (García-Frank et al., 2010). Bioclastic wackestone-packstone of MF1 (Pseudoradiosa Sz.—lowermost Buckmani Sz.) was characterized by relative high diversity and evenness values respectively (6.5 and 5.27; see García-Frank et al., 2010) showing the coexistence of several fossil groups, neither of them dominating over the other. The onset of the bioturbated wackestone of MF2 (Buckmani Sz.—lowermost Bifidatum Sz.) led to a decrease in the number of the microfacies fossil groups (abrupt diminishment in diversity: 4.75), with some groups dominating over others (evenness values of 3.41; see García-Frank et al., 2010) indicate that some of them dominated over the others. This change in the basin conditions reveals that there were processes inhibiting the benthos development. The onset of the bioclastic wackestone-packstone of MF3 (base of Bifidatum Sz.) allowed the increment of diversity and evenness values (6.64 and 4.46 respectively; see García-Frank et al., 2010) allowing the reestablishment of less restricted palaeoecological conditions. This general trend is disrupted by the onset of the mudstone limestone of MF4 (Bifidatum Sz.), with a pulse of lower values of diversity and evenness (5.33 and 3.73 respectively; see García-Frank et al., 2010, where palaeoecological conditions became a bit hostile, but after that returned to the average values of MF3. Finally, the bioturbated mudstone-wackestone of MF5 (Bifidatum SZ.) are recorded. According to García-Frank et al. (2010) it allowed diversity values (5.09) similar to those of the upper part of MF3, but a decrease of evenness with its lowest values within the sect. (2.75). That means that there were several fossil groups, but there was a big dominance of some of them among the others, indicating some kind of restriction in the basin.

In general, the Toarcian–Aalenian transition is remarkably rich in macrofossils, and ammonoids are one of the best represented groups. The ammonite assemblages recorded in the Fuentelsaz section are relatively rich in specimens. Generally, they are well.preserved complete specimens, with the peristome often preserved. This is probably indicative that most of them are accumulated, being less common resedimentation processes. No evidence of reworking has been found. It has been established that the subsequent assemblages are mainly made up of adult and young specimens of the macro- and microconch forms, especially in the Aalensis Zone and the lower and middle part of the Opalinum Zone. Towards the upper part of this zone, ammonites become increasingly scarce, thus being difficult to observe these aspects.

The succession of these assemblages has enabled to recognize and give a detailed definition of all the subzones of the Aalensis Zone (Mactra, Aalensis and Buckmani) in the upper Toarcian and of the Opalinum Zone (Opalinum and Bifidatum) in the lower Aalenian (Cresta et al., 2001; Sandoval et al., 2001) (Fig. 3).

In addition, groups such as brachiopods, foraminifera and palynomorphs, due to their abundance, have allowed the establishment of zonal scales that can be correlated with the ammonoid scale (Fig. 4).

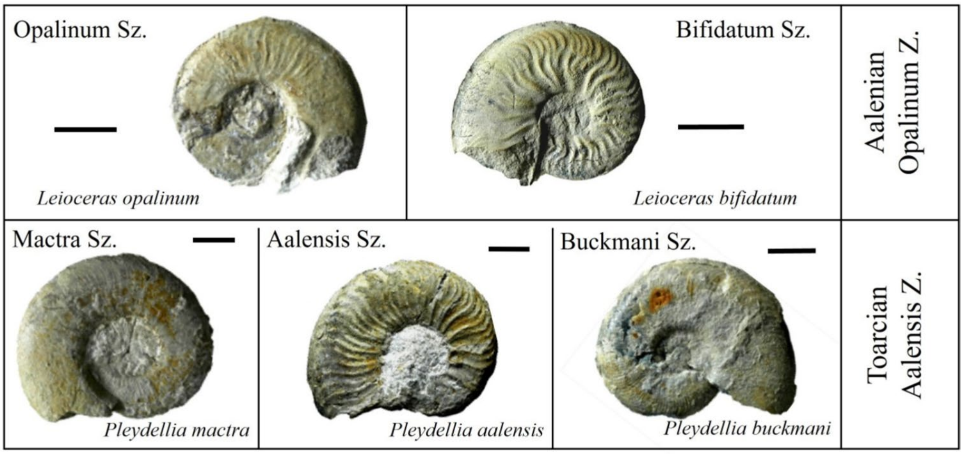


Fig. 5 Index species of the Aalensis and Opalinum zones of Fuentelsaz (Iberian Cordillera). *P. mactra* (Fz44/1), *P. aalensis* (Fz86/1), *P. bukmani* (Fz88/1), *L. opalinum* (Fz108/39) and *L. bifidatum* (Fz130/10). Repository: see Materials and Methods section. Scale bar: 1 cm

Aalensis Zone: Ammonites belonging to the Grammoceratinae and Hammatoceratinae have been recorded in this zone. Lytoceratina is also present, though only sporadically. This zone is basically characterized by the succession of species of the genus *Pleydellia*.

Mactra Subzone: The base has been marked by the first appearance of *Cotteswoldia*. This genus, still in association with the last representatives of the genus *Dumortieria* [*D. costula* (Reinecke) and *D. moorei* (Lycett)] is clearly dominant, both in abundance and diversity, in comparison with other Grammoceratinae, especially *Pleydellia*. Eight species with dissimilar distribution are recorded in the subzone [*C. attrita* Buckman, *C. bifax* Buckman, *C. costula* (Zieten), *C. distans* Buckman, *C. hinsbergi* (Benecke), *C. egena* Buckman, *C. limatula* Buckman, *C. grandjeani* (Benecke)]. As far as the genus *Pleydellia* is concerned, its first representative is *P. mactra* (Dumortier) (Fig. 5), the index species of the subzone, occurring in the lower and middle parts of this unit, being replaced by to *P. subcompta* (Branco) in the upper part.

Aalensis Subzone: It begins with the first appearance of *Pleydellia aalensis* (Zieten) (Fig. 5), a markedly constant species from a biostratigraphic point of view, whose range covers the entire subzone. In its lower part *P. aalensis* (Buckman) appears together with *P. subcompta* (Branco), whereas *P. falcifer* Maubeuge is typical of the upper part. *P. fluens* Buckman also appears sporadically. *Pleydellia* is clearly predominant in this subzone, whereas the genus *Cotteswoldia* is relatively rare, its final representatives [*C. attrita* Buckman, *C. costulata* (Zieten) and *C. hinsbergi* (Benecke)] and *P. subcompta* (Branco) disappearing almost simultaneously. The first representative of the Hammatoceratinae, *Bredyia subinsignis* (Oppel) is found in the upper part of this subzone, a species which constitutes a characteristic form of the Toarcian-Aalenian transition.

Buckmani Subzone: The first record of the index species *Pleydellia buckmani* Maubeuge (Fig. 5) marks the base of this subzone. This species is found throughout the entire unit, ranging up to the base of the next subzone, and is particularly abundant in the terminal levels of the Fuentelsaz section. Other species of *Pleydellia* present are *P. falcifer* Maubeuge and *P. leura* Buckman. This latter species coexists with *P. buckmani* Maubeuge onward from the point of disappearance of *P. falcifer* Maubeuge in the lower part of the subzone. Although scarce, *Bredyia subinsignis* (Oppel) is constantly recorded, and the appearance of a specimen of *Lytoceras* in Fuentelsaz is particularly noteworthy.

Opalinum Zone: Containing ammonites belonging to the subfamilies Leioceratinae, Hammatoceratinae and Grammoceratinae, this zone is basically characterized by the succession of species belonging to the genus *Leioceras*.

Opalinum Subzone: Its base has been marked with the appearance of the first representatives of the genus *Leioceras*, that coexist with the last representatives of the genus *Pleydellia* (*P. buckmani* Maubeuge and *P. leura* Buckman). The species *L. opalinum* (Reinecke) (Fig. 5) and *L. lineatum* Buckman, which presumably belong to the same dimorphic pair, appear simultaneously. The biostratigraphic range of these species extends up to the base of the Bifidatum Subzone. Along with the last two species, with a more restricted distribution range, there are specimens with marked ribs, attributed to the species *L. costosum* (Quenstedt). Together with the two latter species, although with a more restricted range, slightly ribbed *Leioceras*, attributed to the species *L. costosum* (Quenstedt), appears. These forms appear in the same position in other sections of the Iberian Cordillera (cf. Ureta, 1985). As far as the Hammatoceratinae are concerned, *Bredyia subinsignis* (Oppel) is still present.

Bifidatum Subzone: Starts with the first appearance of *Leioceras bifidatum* Buckman (Fig. 5). This is clearly the predominant species. It presents a marked morphological variability that includes almost entirely striated specimens to others that are almost ribbed, all having in common an initial ribbed stage followed by a second striated stage, each of them with variable extension (Goy & Ureta, 1987). Although this species is relatively scarce in the upper levels, its presence has been recorded throughout the entire subzone. In the lower levels, *L. bifidatum* Buckman appears associated with *L. paucicostatum* Rieber, a much infrequent form with ribbed microconch, and in the upper part with *L. crassicostatum* Rieber, also ribbed, and probably macroconch. The presence of *L. uncinatum* Buckman is restricted to the final part and, so far, *Tmetoceras scissum* (Benecke) has only been found in one single level. The most remarkable fact regarding the Hammatoceratinae, is the sharp increase in frequency of *Bredyia subinsignis* (Oppel) in this subzone. *B. fuentelsacensis* Martínez is also recorded in Fuentelsaz for the first time, and this species has been found in a similar biostratigraphic position at various points in the Iberian Range (Martínez, 1992).

Brachiopods are abundant and diverse in the Lower and Middle Jurassic of the Iberian Cordillera and have demonstrated their value as correlation elements. However, the upper Toarcian represents an episode of minimal diversity for this group. At the top of the Pseudoradiosa Zone and the Mactra Subzone of the Aalensis Zone, a single genus with a single species of each of the three large groups (rhynchonellides, terabratulidines and terebratellidines) is record: *Rhynchonelloidea goyi* García-Joral, *Stroudithyris stephanoides* Alméras and Moulan and *Aulacothyris blakei* (Davidson). However, in the Aalensis subzone there is a notable renewal, with the appearance of *Homoeorhynchia cynocephala* (Richard), *Praemonticlarella distercica* García-Joral and *Stroudithyris pisolithica* (Buckman). These species are, in general, more widespread forms and with a more restricted variability, which could be related to the relative stabilization of the environments. After this renewal, there is a progressive increase in diversity, which reached its peak in the Bifidatum Subzone, coinciding with the first presence of several species, such as *Prionorhynchia rubrisaxensis* (Rothpletz), *Neozeilleria anglica* (Oppel) or *Globirhynchia subobsoleta* (Davidson), with a fairly wide geographical distribution. (García Joral & Goy, 1994).

The first attempt to establish a brachiopod-based biozonation for the Lower Jurassic of this basin was proposed by Goy et al. (1984). In this scale, the Toarcian-Aalenian boundary is included within the Cynocephala Zone, which was characterized by the appearance of *Homoeorhynchia cynocephala* (Richard), a species with a wide paleogeographic distribution in the Western Tethys. This zone is preceded by the Infraoolithica Zone, and is subdivided into three subzones (Marini, Blakei and Goyi in successive order) characterized by the first record of *Rhynchonelloidella*? *marini* Rousselle, *Aulacothyris blakei* (Davidson) and *Rhynchonelloidea goyi* García-Joral respectively (Figs. 4, 7).

Subsequently to this work, García Joral et al. (1990) studied in detail the changes in the brachiopod assemblages of the Iberian Cordillera in relation to the paleogeographic changes that took place around the Lower-Middle Jurassic boundary, observing that the important diachronism in the transition between the Turmiel Fm. and the Casinos Fm. in different localities of the basin has a great influence on the distribution of the brachiopod species. *Homoeorhynchia cynocephala* (Richard) is abundant when the sedimentation is predominantly marly in the Aalensis Zone, as in Fuentelsaz, while it is much scarcer when it is more calcareous, where the characteristic species of the previous subzone (*Rhynchonelloidea goyi* García Joral) reaches more recent levels, replacing *Homoeorhynchia cynocephala* (Richard).

However, the association of *Homoeorhynchia cynocephala* (Richard) with other species [*Praemonticlarella distercica* García Joral, *Prionorhynchia rubrisaxensis* (Rothpletz), *Stroudithyris pisolithica* (Buckman), *Neozeilleria anglica* (Oppel)], which constitutes the assemblage 7 defined by García Joral and Goy (2000), allows a good correlation with other nearby basins, so this zone index has been maintained in later reviews (cf. García Joral & Goy, 2010). In this last zonation (based exclusively on rhynchonellides) the Cynocephala Zone is maintained and the Goyi Subzone of the Infraoolithica Zone is raised to the zone rank below it, is represented in. the Fig. 4.

In different sectors of the Iberian Cordillera, the foraminiferal associations recorded in the Lower Jurassic–Middle Jurassic deposits are abundant and diverse (Canales, 2001; Canales & Herrero, 2000; Herrero & Canales, 1997). The representatives of the Suborder Lagenina are predominant, as it is the case of other sections of the marine platforms located in the Jurassic basins of the Northern Hemisphere.

The presence of the species *Astacolus dorbignyi* (Roemer) (Fig. 7) in the Iberian Cordillera and the other Peri-Iberian basins considered in this work, has allowed the recognition of the *Astacolus dorbignyi* Zone, which extends from the Mactra Subzone (upper Toarcian) to the lower boundary of the Bradfordensis Subzone (middle Aalenian), coinciding with the first record of *Lenticulina quenstedti* (Gümbel), index species of the Lenticulina quenstedti Zone (Fig. 4). The species *Astacolus dorbignyi* (Roemer) has been historically used in different Mesozoic basins of the Northern Hemisphere as an index species characteristic of the upper Toarcian (Bartenstein & Brand, 1937) and especially of the Aalenian (Bejjaji et al., 2010; Boutakiout, 1990; Copestake & Johnson, 1984; Exton & Gradstein, 1984; Gradstein, 1977, 1978; Tyszka, 1999; Wernli & Septfontaine, 1971). In the Aragonese Branch of the Iberian Cordillera (Moyuela section), Canales and Herrero (2000) identified its presence in the upper Toarcian, specifically in the Insigne Zone (Insigne Subzone). The first record of this species has been identified in deposits from the Variabilis Zone, Illustris Subzone, although these records are sporadic and not very abundant (Oliva, pers. comm). Likewise, the abundance of specimens of this species generally decreases from the Murchisonae Zone onwards, which, together with the first record of *Lenticulina quenstedti* (Gümbel), means that *Astacolus dorbignyi* (Roemer) allows us to recognize the stratigraphic interval between the upper Toarcian Mactra Subzone and the basal part of the middle Aalenian Bradfordensis Zone. As indicated above, this species is a common component in the foraminiferal associations of this stratigraphic interval both in the different basins of the Iberian Plate and in the Boreal Domain. This, together with their distinctive morphological features, which allow the identification of this taxon, even in the case of broken or relatively poorly preserved specimens, make this species and excellent index fossil for this stratigraphic interval.

In some areas of the Iberian Cordillera, the Lenticulina quenstedti Zone, whose beginning in other peri-Iberian basins coincides with the base of the Bradfordensis Zone, is not always easy to recognize, mainly due to the absence of records. This is the case of the Fuentelsaz section, where the Jurassic successions ends in deposits from the Bifidatum Subzone (Goy et al., 1994), or of the Moyuela section (Canales & Herrero, 2000), where a hiatus is recorded affecting most of the middle and upper Aalenian deposits. In the Hontoria del Pinar section, where the data are preliminary so far (Canales et al., 2013), the first record of *Lenticulina quenstedti* (Gümbel) occurs at the base of the upper Aalenian (Convavum Zone, Concavum Subzone). However, in the Demanda-Cameros sector, where the Muro de Aguas (Canales, 2001) and Talveila (Hernández, 2015; Hernández et al., 2018) sections have been studied, the first record of *Lenticulina quenstedti* (Gümbel) occurs at the base of the Bradfordensis Zone, highlighting its usefulness as an index species in the Mesozoic basins of the Iberian Plate. Barbieri (1964) established the Lenticulina quenstedti Zone in Sicily (Italy) from the base of the Bajocian and Boutakiout (1990) established the *Lenticulina quenstedti* mg *Lenticulina* Biozone in Rift deposits from Morocco, also coinciding with the base of the Bajocian.

The ostracod associations of the Fuentelsaz section are similar in their taxonomic composition to those of NW Europe at the genus level, as they consist of different species of *Praeschuleridea* and with similar stratigraphic ranges. The only major discrepancy is the absence of *Aphelocythere kuhni* (Ohmert) in the Fuentelsaz section, which marks the boundary between the Toarcian and Aalenian in some other European areas (Knitter & Riegraf, 1984; Ohmert, 2004). The distributions of the ostracod associations show a significant faunal change due to the latest occurrence of twelve species throughout the Aalensis Zone of which *Praeschuleridea ventriosa* (Plumhoff) and *Eucitherura tricostata* (Michelsen) can be highlighted. The eight species recorded in the Opalinum Zone extend their distribution range from the Aalensis Zone; however, *Kinkelinella fischeri* (Malz) is one of the most characteristic species of this zone (Fig. 7). The zonal scale of Lower Jurassic ostracods was proposed by Ohmert (2004), in which the Toarcian-Aalenian boundary is located within the Kuhni Zone (Fig. 4), whose base coincides approximately with the base of the Aalensis Subzone and its top is at the end of the Bifidatum Subzone. The zonal index species *Aphelocythere kuhni* (Ohmert) has so far not been found in the section (Arias et al., 2009).

The study of the Fuentelsaz section shows palynomorph assemblages taphomically biased. According to Spicer (1991) and Davis (2000), the palynological content in sediments depends on various factors including the type of plant producer, their productivity, the hydro/aerodynamic properties of the palynomorphs, the distance from the source area, the rate of sedimentation, the grain size of sediments and the presence of carbonates and/or organic matter. Concretely, the assemblages inferred in Fuentelsaz section were recovered in marly levels associated with shallow marine carbonate platform facies deposited in an extensive marine epeiric carbonate platform around 50 km to the coasts of the Iberian Island (Barrón et al., 2010). These circumstances were responsible that, on the one hand, they are numerically dominated by wind-transported pollen of gymnosperms (*Spheripollenites psilatus* Couper and *Classopollis* spp.; Batten & Dutta, 1997; Peyrot et al., 2007) and the conspicuous occurrence of acanthomorphs acritarchs of the genus *Micrhystridium*, which indicates a partly enclosed, shallow, inshore environments (Schrank, 2003). On the other hand, the assemblages of Fuentelsaz section exhibit low diversity of taxa (7 types of aquatic palynomorphs and 37 miospores) what is similar to the record obtained in the near Mid-Jurassic place at the Camarena Island (Santos et al., 2024), being very different to the described in other Aalenian sites from the Proto-Atlantic Iberian coasts (Correia et al., 2019) and other Boreal and Austral regions (see Barrón et al., 2010 and references herein). The reasons for this different composition may be related to the shallow platforms that developed in the western margin of the Peri-Tethyan basin on the progressively submerging Iberian Block (Gomez & Goy, 2005). In addition, this Block was located in the Northern Hemisphere, in the north part of a subtropical desert climatic band (Dera et al., 2009).

Five successive palynological assemblages (Pa) were inferred (Barrón et al., 2010): (1) The oldest one (Pa1) coincides with the Insigne Subzone and it is characterized by high percentages of *Classopollis* (60–80%). (2) The Pa2 includes the Pseudoradiosa and the Mactra subzones, as well as the lower middle part of the Aalensis Subzone. It is numerically dominated by *Spheripollenites psilatus* Couper (45–90%) showing lower, but relevant percentages of *Classopollis* (around 20–40%). (3) Very high percentages (> 85%) of *S. psilatus* Couper and low presence of

Classopollis (< 15%) determine the Pa3 which comprises the upper middle part of the Aalensis Subzone and the most part of the Buckmani Subzone. It is conspicuous the presence of *Micrhystridium lymensis* Wall with values close the 10%. (4). The Pa4 corresponds with the Toarcian–Aalenian boundary and it includes the uppermost part of the Buckmani Subzone and the Opalinum Subzone. Its palynological content is similar to Pa2 showing values of 55–80% of *S. psilatus* Couper and 20–45% of *Classopollis*. (5) Finally, the Aalenian Bifidatum Subzone is characterized by percentages higher than 90% of *S. psilatus* Couper, very weak presence of *Classopollis* (< 2%) and conspicuous occurrence of *M. lymensis* Wall (Pa5) (Figs. 4, 7).

3.2 Basque-Cantabrian Cordillera

The Toarcian-Aalenian transition show remarkable thickness variations in the different outcrops studied. In the southwestern part there is a local hiatus that affects the end Toarcian and the basal Aalenian. The depocenter of the basin is located in the central part of this region, reaching the greatest thickness of the Basque Cantabrian Cordillera as a whole. The continuous and expanded stratigraphical successions of the Lower-Middle Jurassic transition in this area can be typified by the San Andrés and Pujayo sections (Gómez et al., 2009; Goy & Ureta, 1994; Goy et al., 2006). In these sections where the most complete ammonoid successions have been found. From a lithological and sequential point of view, this interval is represented by rhythmic successions of marly limestones and hemipelagic marl limestones, arranged in shallowing upward sequences, which belong to the Castillo Pedroso Fm. (Quesada et al., 2005). This formation was deposited in an outer platform environment (Gómez et al., 2009). The ammonoid successions are constituted by associations rich in specimens with remarkable diversity.

In the Upper Toarcian (Aalensis Zone), the Mactra, Aalensis and Buckmani subzones have been identified and within the Lower Aalenian (Opalinum Zone), the Opalinum and Bifidatum subzones (Fig. 3).

Aalensis Zone: It is characterized by the appearance and development of different species of the genus *Pleydellia* that characterize each of the recognized subzones.

Mactra Subzone: It is recognized by the first occurrence of *Pleydellia mactra* (Dumortier) found in the lower half of this subzone. It is replaced by *Pleydellia subcompta* (Branco) that characterizes the upper part. These species coexist with the genus *Cotteswoldia* that extends its range throughout the subzone.

Aalensis Subzone: It begins with the first record of *Pleydellia aalensis* (Zieten), a notably abundant species throughout the subzone. It coexists in its lower part with *Pleydellia subcompta* (Branco) and the last *Cotteswoldia* representatives. In the upper part of the subzone appears *Pleydellia fluens* Buckman and *P. falcifer* Maubeuge.

Buckmani Subzone: It is characterized by a decrease in the abundance of ammonoids. It begins with the first record of *Pleydellia buckmani* Maubeuge that extends its range to the uppermost part of the subzone together with *P. leura* Buckman. In the lower part, the last specimens of *Pleydellia falcifer* Maubeuge are recorded. It is remarkable the appearance in this subzone of elements with Mediterranean affinities such as the genera *Vacekia* and *Bredyia*. Specifically, *Vacekia sourensis* Perrot and *Bredyia subinsignis* (Oppel) are found in the upper half.

It is interesting to note that *P. mactra-P. subcompta-P. aalensis-P. falcifer-P. buckmani* constitute a phyletic lineage whose range extends throughout the Aalensis Zone.

Opalinum Zone: It is characterized by the appearance and development of the genus *Leioceras* whose species characterize the two recognized subzones.

Opalinum Subzone: It begins with the first record of *Leioceras opalinum* (Reinecke). This species coexists with its probable dimorphic form, *Leioceras lineatum* Buckman and their ranges extend throughout the subzone. Alongside these species, *Bredyia subinsignis* (Oppel) is still found throughout the interval and at the extreme top is *B. lotharingica* (Branco).

Bifidatum Subzone: It is recognized from the first appearance of *Leioceras bifidatum* Buckman, a species that extends its range to the uppermost part of the same subzone. In the upper part appear the already clearly ribbed specimens of *Leioceras* such as *Leioceras paucicostatum* Rieber, *L. uncinatum* Buckman and *L. crassicostatum* Rieber. It is noteworthy that the first specimens of the genus *Ancolioceras* appear also at the top. The genus *Tmetoceras* and specifically *T. scissum* (Benecke) early appears in the lower part of the subzone, just after the last specimens of *Bredyia subinsignis* (Oppel), and its range extends to the extreme base of the Murchisonae Zone. In the upper part, there are also clearly Mediterranean elements such as *Spinammatoceras pugnax* (Vacek) and the genus *Lytoceras*.

Brachiopods from the Lower-Middle Jurassic boundary have been studied in Asturias and the Basque-Cantabrian Basin by García Joral and Goy (2009a, 2009b a, b). After the extinction of the Lower Toarcian, assemblages different from those of the Iberian Cordillera appeared in these basins. In the Variabilis Zone, two species appear for the first time in several localities: *Pseudogibbirhynchia bothenhamptonensis* (Walker), which is recorded up to the Aalensis Zone, and *Soaresirhynchia renzi* (Choffat), which extends to the Insigne Subzone of the Dispansum Zone, where it can be very abundant. In addition to these two species, specimens of *Neozeilleria lycetti* (Davidson) in the Dispansum Zone, *Praemonticlarella* n. sp. in the Dispansum and Pseudoradiosa zones, as well as *Neozeilleria* sp. and *Homoeorhynchia* *cynocephala* (Richard) in the Aalensis Zone, have been sporadically recorded. No brachiopods were found in the Opalinum Zone.

These species have been considered by Andrade et al. (2016) as belonging to a new paleobiochore: the Iberian-Atlantic District, that covers the sedimentary area located at the north and west borders of the Iberian Massif, including Asturias and the Lusitanian and Basque-Cantabrian basins. This paleobiochoreis differentiated from an Iberian-Mediterranean District, recognized in the Iberian Basin and in the Catalan Basin. The boundary between these two districts can be established according to paleontological and stratigraphic criteria between the Castillo Pedroso Fm. of the Basque–Cantabrian Basin and the Turmiel Fm. and Casinos Fm. of the Iberian Cordillera.

In the zonation based on rhynchonellides proposed by García Joral and Goy (2010), three zones have been defined based on the distributions observed in these basins: Renzi Zone, characterized by the appearance of *Soaresirhynchia renzi* (Choffat) associated with *Pseudogibbirhynchia bothenhamptonensis* (Walker); *aff.* Distercica Zone, characterized by the appearance of *Praemonticlarella* n. sp. aff. *distercica* García Joral; and Cynocephala Zone, characterized by the appearance of *Homoeorhynchia cynocephala* (Richard) (Figs. 4, 7). This last zone allows the correlation with the Iberian Basin and other European basins.

The foraminiferal associations of the Lower-Middle Jurassic transition of the Basque-Cantabrian Basin were first studied in detail by Canales (2001). These associations are made up of a large number of specimens and taxa, generally well preserved, in which representatives of the Suborder Lagenina predominate, which, as in the rest of the Peri-Iberian basins and other contemporary basins of the Northern Hemisphere, show a high abundance and diversity. Detailed analysis of the stratigraphic distribution of the species identified in a total of 7 sections of this basin allowed us to establish a zonal scale based on this group of microfossils, well-calibrated with the ammonoid scale (Fig. 4). Specifically, for the stratigraphic interval between the Upper Toarcian (Aalensis Zone, Mactra Subzone) and the Lower Aalenian (Opalinum Zone, Bifidatum Subzone), the Astacolus dorbignyi Zone was proposed, whose upper limit coincides with the base of the Bradfordensis Zone, when the first record of *Lenticulina quenstedti*, index species of the Lenticulina quenstedti Zone, occurs. As noted above, in other basins of the Boreal Domain the species *Astacolus dorbignyi* (Roemer) (Fig. 7) has been used to establish a biozone extending throughout the Aalenian, while the species *Lenticulina quenstedti* (Gümbel) has been proposed to characterize the base of the Bajocian.

In addition, in the Basque-Cantabrian Basin Canales (2001) established 3 biohorizons in the Astacolus dorbignyi Zone: the Biorizon exgaleata, determined by the first record in the studied sections of the species *Lenticulina exgaleata* Dieni, which extends from the Mactra Subzone (Aalensis Zone, Upper Toarcian) to the first record of the species *Falsopalmula uretae* Canales, which occurs in the middle part of the Bifidatum Subzone (Opalinum Zone, Lower Aalenian), being the index species of the Biohorizon Uretae. This biohorizon is short-lived and extends from the middle part of the Bifidatum Subzone to the base of the Murchisonae Subzone (Murchisonae Biozone, Middle Aalenian), coinciding with the first record of the species *Vaginulina herrerae* Canales, nominal index species of the Herrerae Biohorizon. Its extension is also very short and is limited to the Murchisonae Subzone, ending with the first record of the species *Lenticulina quenstedti* (Gümbel). Subsequent studies have shown that the species *Falsopalmula uretae* Canales and *Vaginulina herrerae* Canales have a very limited record outside the Basque-Cantabrian Basin. Thus, the species *Vaginulina herrerae* Canales has only been found punctually in Santa Mera, in Asturias (Silva, 2020) and in the Talveila section, in the Iberian Cordillera (Hernández, 2015). Therefore, the applicability of these biohorizons is restricted to the basin scale.

3.3 Lusitanian Basin

The Toarcian-Aalenian boundary is well-represented in the northern sector (Cabo Mondego, Coimbra and Degracias region). The São Gião section, near Coimbra, is representative of the general zonal scheme (Fig. 3), recognized in other sections of the Lusitanian Basin (Henriques et al., 1996; Henriques, 1992, 1995, 2000a). In this section the Toarcian-Aalenian transition, which is integrated into the Póvoa da Lomba Fm., corresponds to a strong interval of marly limestones (more than 40 m) that develop in four sequences, in which the frequency of limestones increases towards the upper part. The ammonoid associations include NW and Mediterranean taxa in almost equal proportions. In the Upper Toarcian it is possible to recognize the Aalensis Zone (11 m thick) with the Mactra and Aalensis subzones. Marls and marly limestones are dominant and resedimented ammonites are very abundant (incomplete adult shells in the calcareous levels and pyritized nuclei in the marls). In the Lower Aalenian, the Opalinum and Bifidatum subzones of the Opalinum Zone (36 m thick) can be recognized. From the Bifidatum Subzone onwards, characteristic ammonoids are rare, but Mediterranean forms such as *Vacekia* become abundant.

In the Toarcian-Aalenian transition of the Lusitanian Basin, the marked paleoenvironmental differences between the most proximal and most distal sectors involve brachiopod faunas and, in the shallower areas closest to the continent, only *Stroudithyris stephanoides* Alméras & Moulan, a widespread species present in the Iberian Cordillera, appears in the Upper Toarcian. In the sections corresponding to the most distal areas of the basin, in the Upper Toarcian, the species recorded are similar to those of Asturias and the Basque-Cantabrian Basin, especially *Soaresirhynchia renzi* (Choffat) and *Pseudogibbirhynchia bothenhamptonensis* (Walker), characteristics of the Ibero-Atlantic District explained above. Together with these species, other endemic species of the Lusitanian Basin appear, such as *Pamirorhynchia*? *jorali* Andrade, *Nannirhynchia cotteri* Choffat, *Praemonticlarella conimbrigensis* Andrade or *Neozeilleria duartei* Andrade (cf. Andrade, 2006). In the Aalensis Zone only one of these species survives, *Pamirorhynchia*? *jorali* Andrade, and *Nannirhynchia nuskae* Andrade appears at the top of the Meneghinii Zone. The disappearance of *Nannirhynchia nuskae* Andrade at the end of the Aalensis Zone marks the beginning of an interval with no brachiopod record in the entire basin that includes the Opalinum Subzone and part of the Bifidatum Subzone of the Opalinum Zone. This episode is followed by a new brachiopod assemblage, containing species native to the basin (*Soaresirhynchia minor* Andrade, *Soaresirhynchia murtinheirensis* Andrade) together with others present in other European basins such as *Pseudogibbirhynchia mutans* (Rothpletz), *Sphaeroidothyris uretae* García Joral, or *Lophrothyris withingtonensis* (Buckman).

As a consequence of the high number of endemisms, the zonal scale based on brachiopods proposed by Andrade (2006) is composed of zones defined by species native to the basin. The Toarcian-Aalenian boundary is situated within the Nuskae Subzone of the Anglica Zone, characterized by the occurrence of *Nannirhynchia nuskae* Andrade, whose lower boundary is slightly below the base of the Aalensis Zone. Above, the Anglica Subzone begins in the middle part of the Bifidatum Subzone (Figs. 4, 7). Below the Anglica Zone is the Renzi Zone, whose lower subzone (Renzi Subzone) is equivalent to the Renzi Zone in Asturias and the Basque–Cantabrian Basin.

The foraminiferal associations of the Upper Toarcian-Lower Aalenian interval of the São Gião section are the most abundant and diverse of all the sections analyzed in different Jurassic basins of the Iberian Plate (Henriques & Canales, 2013). They consist of very well preserved specimens and, in most of them, a clear predominance of representatives of the Suborder Lagenina is observed. However, a significant increase of representatives of the Suborder Miliolina in the lower part of the Bifidatum Subzone stands out, probably related to a local increase in water temperature. The abundant and constant presence of the species *Astacolus dorbignyi* (Roemer) in the studied associations has allowed us to recognize the Astacolus dorbignyi Zone (Figs. 4, 7). This zone has also been recognized in other sections studied in different sectors of the Lusitanian Basin, including the Murtinheira section, where Bajocian GSSP is defined (Canales & Henriques, 2008) and the Maria Pares section (Guterres, 2010), both in the Northern Sector of the basin, and in the Zambujal de Alcaria section (Figueiredo et al., 2010), located in the Central Sector of the basin. The constant presence of the index species, *Astacolus dorbigny* (Roemer) in all these sections, which were located in very different points of the basin (Canales et al., 2014), highlights the independence of this taxon in relation to the facies type.

In these three sections (Murtinheira, Maria Pares and Zambujal de Alcaria), the upper limit of the Astacolus dorbignyi Zone coincides with the first record of the species *Lenticulina quenstedti* (Gümbel), occurring at the base of the Bradfordensis Subzone (Bradfordensis Zone, Middle Aalenian), as it happens in the sections of the Basque-Cantabrian Basin and in many of the sections of the Iberian Cordillera, showing the applicability of these biozones based on foraminifera in the Peri-Iberian basins. As was the case in some sections of the Iberian Cordillera, in both the São Gião section and the Serra da Boa Viagem section (Silva et al., 2015a) the latter biozone could not be identified due to lack of sedimentary record.

The palynofloras from the Toarcian-Aalenian transition at São Gião are relatively sparce and poorly preserved and are dominated by gymnosperm pollen. Material from coeval levels at Cabo Mondego section (Cabo Mondego Fm.) display moderately well-preserved specimens, mainly of foraminiferal test linings and gymnosperm pollen, all typical of the Toarcian and Aalenian worldwide. The most remarkable feature is the diversification and proeminence of Araucarian pollen, mainly *Callialasporites*, during the Aalenian. The Toarcian–Aalenian stratigraphical interval records dinoflagellate cysts assemblages displaying low diversity, characterized by the occurrence of *Nannoceratopsis* representatives, markedly less diverse than coeval assemblages from eastern and northern Europe, and the Artic (Correia et al., 2019).

3.4 Betic Cordillera

The Lower-Middle Jurassic transition (upper Toarcian/lower Aalenian), Aalensis and Opalinum ammonite zones, is well-developed in several areas of the Median Subbetic subdomain with a thickness that can reach 35 m. For the analysis of this interval, the more representative stratigraphic sections are located in Sierra de Ricote (JRi1 section), Ricote, Murcia Region; Barranco de Agua Larga (JAQ1 section), in Noalejo, Jaén Province, and in Cerro Méndez area (CM, CM1, CM2 sections), Granada and Jaén provinces (García-Gómez et al., 1994; Linares & Sandoval, 1993; Sandoval et al., 2008, 2011, 2012a, 2015, 2020). In all the aforementioned localities, the upper Toarcian (Aalensis Zone) and lower Aalenian (Opalinum Zone) materials are mostly made up by alternations of whitish-grey marls, marly limestones and limestones. Limestone or marly-limestones predominates in the

Aalensis Zone and in the Bifidatum Subzone, whereas the marls dominate in the Opalinum Subzone, which frequently has little thickness.

Locally, in the Upper Toarcian (Mactra Subzone) and in the Lower Aalenian (Bifidatum Subzone) of some Median Subbetic localities occur nodular calcareous or marly–calcareous facies, which generally have small thickness, whereas in several localities of the Internal and External Subbetic, this time interval coincides with hiatuses linked to sedimentary gaps (Linares & Sandoval, 1993; Sandoval et al., 2008, 2012a).

Abundant trace fossils, especially *Chondrites* and *Zoophycos*, are found throughout the sections, with the latter being especially abundant just in the Toarcian/Aalenian boundary. Microfacies of the compact beds (limestones or well-compacted marly-limestones) are mudstones to wackestones with well-preserved radiolarians, thin-shelled bivalves (*Bositra*), with benthic foraminifers and ostracods being less abundant. Benthic foraminifers, thin-shelled bivalves and calcareous nannofossils are common in the marly beds.

The ammonite assemblages are rich in number of specimens, very diversified; and generally, with relatively well-preserved taxonomic characters. In some localities, mostly internal moulds, appear lying sub-horizontal, quite flattened by lateral symmetrical compression. In the most expanded stratigraphic sections such as Cerro Méndez and Sierra de Ricote (see Sandoval et al., 2012a, 2020), and for taxa in which dimorphism is apparent, macroconchs and microconchs, both juveniles and adults, appear almost equivalently and without demonstrable evidence of taphonomic reworking or post-mortem transport. The successive assemblages of ammonites which are dominated by grammoceratins, harpoceratins, hammatoceratids and erycitids in the upper Toarcian and by leioceratins, tmetoceratins and erycitids in the lower Aalenian allowed to separate the Aalensis Zone (Mactra, Aalensis and Buckmani subzones) in the uppermost Toarcian and the Opalinum Zone (Opalinum and Bifidatum subzones) for the lower Aalenian; phylloceratids and lytoceratids, although not dominant, are common throughout the interval (Linares & Sandoval, 1993; Sandoval et al., 2008, 2011, 2012a, 2012b, 2015, 2020).

In the Betic Cordillera, the Hammatoceratoidea (erycitids and hammatoceratids) are very well represented, which made it possible to establish a biozonation based on these elements (Sandoval et al., 2011), that easily can be correlated with the standard zonation. The general revisions of Hammatoceratidae and Erycitidae (Martínez et al., 2015; Sandoval et al., 2015, 2020) carried out after the aforementioned paper, make it necessary to review and update this biozonation. The biozones of the uppermost Toarcian and lower Aalenian that were defined and characterized by Sandoval et al. (2011) and that now are reviewed here are (Figs. 3, 6):

3.4.1 Biozone of ***Crestaites meneghinii*** (Sandoval et al., 2011)

Although the base of the biozone is marked by the first record of *Crestaites meneghinii* (Bonarelli), the biozone is characterized primarily by the association of different *Crestaites* and *Geczyceras* species, besides of primitive *Erycites* and scarce *Hammatoceras* and *Planammatoceras*: *Crestaites victorii* (Bonarelli), *Geczyceras speciosum* (Janensch), *G. perplanum* (Prinz), *G. allobrogense* (Dumortier), *G. porcarellense* (Bonarelli), *Hammatoceras semilunatum* (Quenstedt, 1885) and *Planammatoceras* sp. aff. *P. tenuinsigne* (Vacek) in Sandoval et al. (2020). *Cagliceras elaphum* (Merla), *C. rotundiformis* (Merla), the oldest erycitids, also occur in this biozone. Several of the aforementioned species extend their stratigraphic range into the biozone immediately below.

Although the boundaries do not exactly coincide, this biozone almost corresponds with the standard Meneghinii Zone (see Sandoval et al., 2011 and references therein). The stratigraphic range of this biozone includes the Meneghinii (Levesquei Subzone *p.p.* and Pseudoradiosa Subzone) and Aalensis Zone (Mactra Subzone *p.p.*) of the standard ammonite zones.

3.4.2 Biozone of ***Erycites barodiscus*** (Sandoval et al., 2011)

The lower boundary is marked by the first record of *Erycites barodiscus* (Gemmellaro) which occurs associated with *Planammatoceras metellii* (Gemmellaro) and *Bredyia subinsignis* (Oppel). In the lower part of the biozone are common

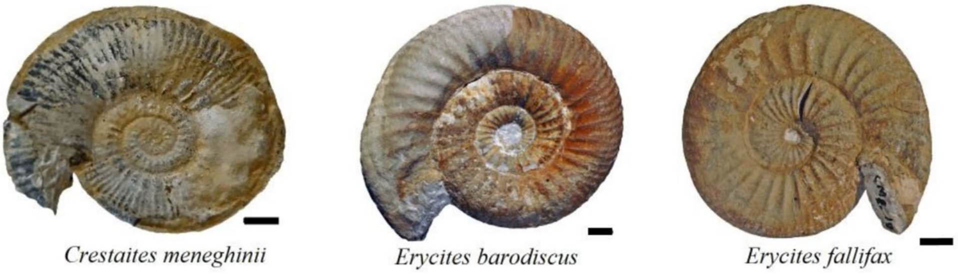
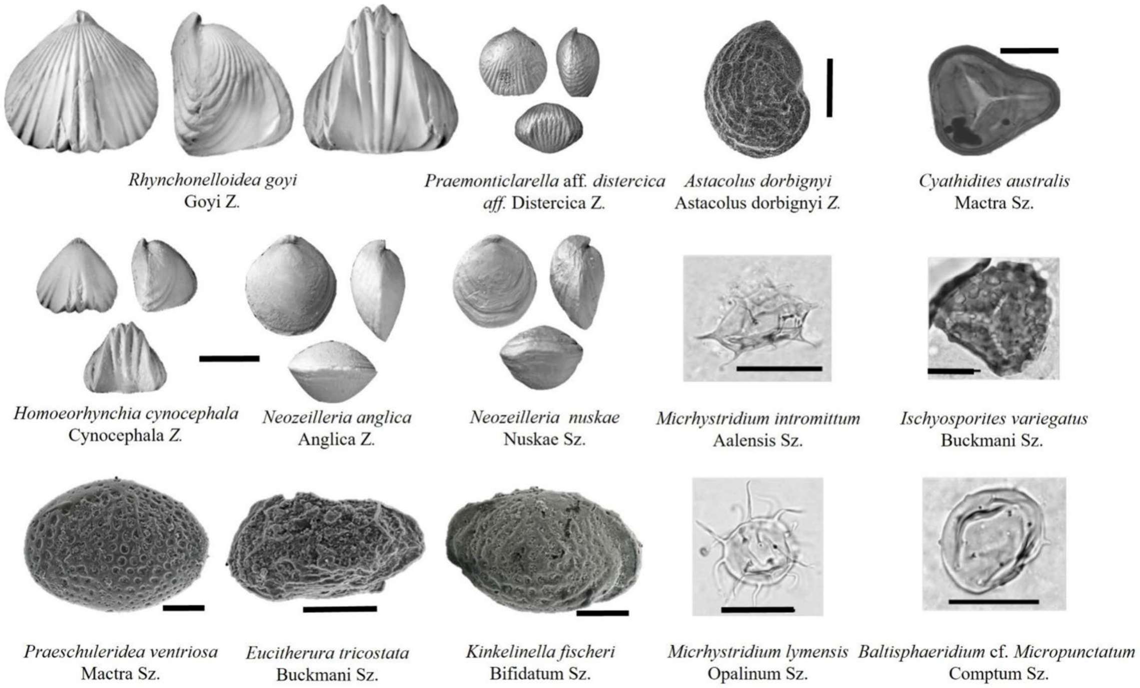


Fig. 6 Index species of the *Crestaites meneghinii*, *Erycites barodiscus* and *Erycites fallifax* biozones in the Betic Cordillera (Cerro Méndez section). *C. meneghinii* (CM.35B.1), *E. barodiscus* (CM.66.2) and *E. fallifax* (CM2.19.1). Repository: see Materials and Methods section. Scale bar: 1 cm



Rhynchonelloidea goyi
Goyi Z.

Praemonticlarella aff. *distercica*
aff. Distercica Z.

Astacolus dorbignyi
Astacolus dorbignyi Z.

Cyathidites australis
Mactra Sz.

Homoeorhynchia cynocephala
Cynocephala Z.

Neozeilleria anglica
Anglica Z.

Neozeilleria nuskae
Nuskae Sz.

Micrhystridium intromittum
Aalensis Sz.

Ischyosporites variegatus
Buckmani Sz.

Praeschuleridea ventriosa
Mactra Sz.

Eucitherura tricostata
Buckmani Sz.

Kinkelinella fischeri
Bifidatum Sz.

Micrhystridium lymensis
Opalinum Sz.

Baltisphaeridium cf. *Micropunctatum*
Comptum Sz.

Fig. 7 Index or significant species of the zones and subzones established in the different basins referred in this work based on brachiopods (Scale bar: 1 cm), foraminifera (Scale bar: 100 µm), palynomorphs (Scale bar: 10 µm) and ostracods (Scale bar: 100 µm).

Geczyceras costulosum (Merla), *"Planammatoceras"* sp. A in Sandoval et al. (2020) and *Geczyceras tipperi* (Seyed-Emami) while *Bredyia alleoni* (Dumortier) and *B. rhodanica* (Renz) occur only in the upper part of the biozone. As indicated by Sandoval et al. (2011), this biozone ranges the Aalensis Zone (Mactra *p.p.*, Aalensis and Buckmani subzones) and the Opalinum Zone (Opalinum Subzone) of the standard ammonite zones. In Sandoval et al. (2011), the correlations of this biozone with the ammonite biostratigraphy established in other Mediterranean and Submediterranean areas are discussed.

3.4.3 Biozone of *Erycites fallifax* (Sandoval et al., 2011)

The base of this biozone was defined by the first record of *Erycites fallifax* Arkell. The index species commonly occurs together with *Spinammatoceras pugnax* (Vacek), its possible microconch, *Abbasitoides compressus* (Prinz), *Planammatoceras planinsigne* (Vacek)*, P. tenuinsigne* (Vacek), *P. rulleaui* (Sandoval et al., 2020), *Paviaites* sp. aff. *Paviaites iris* (Gemmellaro), *Accardia procerinsigne* (Vacek), *A. liebi* (Maubeuge) and, *Accardia* sp. A in Sandoval et al. (2020). As indicated by Sandoval et al. (2011), the biozone of *Erycites fallifax* is almost equivalent to the upper part of the Opalinum Zone (Bifidatum Subzone) of the standard ammonite zones, although some specimens of *E. fallifax* can occur in the lowermost part of the Murchisonae Zone.

Apart from ammonites, the only representative macrofossils for this stratigraphic interval are belemnites, but these are never abundant. Also, besides of the aforementioned finely shelled (*Bositra*), bivalves are virtually absent in the Toarcian-Aalenian interval of the Betic Cordillera.

Brachiopods are abundant fossils in the Lower Jurassic of the Betic Cordillera, but, as in many other basins of the Mediterranean Province, they almost completely disappear from the record after the Early Toarcian Mass extinction. There are sporadic records of species corresponding to the "Spanish Fauna" (Baeza-Carratalá, 2013; Baeza-Carratalá et al., 2011a) corresponding to the Serpentinum Chronozone, and they are not represented again until the Bajocian (Baeza-Carratalá et al., 2011b, 2014).

Studies on foraminifera of the stratigraphic interval considered in this work are scarce in the Betic Cordilleras and have begun to be developed recently. It is worth mentioning the PhD Thesis of Mira (1986) on the Lower Jurassic foraminifera of the Subbetic Zone. This author referred to the foraminifera of the Lower Jurassic-Middle Jurassic transit in some sections and established the Lenticulina tenuistriata Zone in the materials of the Toarcian-Aalenian transition (Aalensis Zone-Opalinum Zone). The work carried out to date in the Cerro Méndez section, although preliminary (Romero & Canales, 2022), shows that the foraminiferal associations of the Toarcian-Aalenian transition are very abundant and diverse. They show a predominance of representatives of the Suborder Lagenina, as in the rest of the sections of the analyzed basins. However, compositional changes are observed at the genus level, highlighting a high abundance and diversity of representatives of the genus *Prodentalina*. This abundance has also been observed in the Middle Aalenian-Lower Bajocian foraminiferal associations studied in the Agua Larga section (Silva, 2020; Silva et al., 2015b). From a biostratigraphic point of view, the index species *Astacolus dorbignyi* (Roemer) (Figs. 4, 7) and *Lenticulina quenstedti* (Gümbel) have been identified in the Cerro Méndez and Agua Larga sections, so it seems feasible that the foraminiferal biozones established and applicable in the rest of the Peri-Iberian basins can also be used in the Betic Cordillera. However, it is necessary to continue the works in course to be able to confirm this.

4 Correlations

The correlation between the standard scale of ammonoids and the different scales established for the basins of the Iberian Peninsula is represented in Figs. 3 and 4.

Since the 1970s, reference scales have been used for the Toarcian–Aalenian transition, including the Aalensis and Opalinum zones established with the first record of the genus *Pleydellia* and the first record of the genus *Leioceras*, respectively. The subdivision of these zones was made taking into account the evolution of the species of the above-mentioned genera. The subdivision of the Aalensis Zone into Mactra, Aalensis and Buckmani subzones was used in the Basque-Cantabrian Basin, Iberian and Betic Cordilleras, by Suárez-Vega (1974), Goy (1985), Goy et al., (1988, 1994, 2006, Goy et al., 2010), Elmi et al. (1989), Goy and Martínez (1990), among others. In the Lusitanian Basin, the Aalensis Zone has been subdivided into Mactra Subzone and Aalensis Subzone by Henriques (1992, 1995, 2000b) and Sandoval et al. (2001).

The subdivision of the Opalinum Zone into Opalinum Subzone and Comptum Subzone (Bifidatum Subzone in this work), was used by Fernández-López and Suárez-Vega (1980), Goy and Ureta (1981), Ureta (1985), Goy (1985), Fernández-López et al. (1988), Linares et al. (1988), Goy and Ureta (1990), Henriques (1992), Linares and Sandoval (1993), Henriques (2000b), Henriques et al. (1996), Goy et al., (1994, 2006), Cresta et al. (2001), Sandoval et al. (2001), and Gómez et al. (2009), among others.

Regarding brachiopods, the paleobiogeographic differentiation observed in this time interval (cf. Andrade et al., 2016) makes correlation between the different basins difficult. However, the presence of *Homoeorhynchia cynocephala*, a species widespread throughout the Western Tethys and recognized in the Iberian Cordillera and Basque–Cantabrian basin and, punctually, in the Lusitanian Basin, can be considered a good correlation element.

The first zonal scale based on foraminifera from the upper Toarcian-lower Aalenian in Spain was established by Canales (2001) in the Basque-Cantabrian Basin. For this interval, the Astacolus dorbignyi Zone was established, already recognized in other European basins, with a wider stratigraphic range, since it extended from the upper Toarcian to the Aalenian-Bajocian boundary. However, in the Basque-Cantabrian Basin, the Lenticulina quenstedti Zone was also defined for the stratigraphic interval from the Bradfordensis Subzone (Bradfordensis Zone, middle Aalenian) to the Laeviuscula Biozone in the Lower Bajocian. Subsequent studies in the Iberian Cordillera and in the Lusitanian Basin have recognized these biozones, thus confirming their validity at the scale of the Iberian Plate. Ongoing studies in the Betic Cordillera seem to indicate that these zones can also be recognized there. The biohorizonts established by Canales (2001) in the Basque-Cantabrian Basin have been recognized, confirming their validity at the basin scale in the Iberian Plate.

With respect the palynomorphs, the occurrence of assemblages integrated by taxa with long stratigraphic ranges, as well as, the low diversity of the studied assemblages make difficult the correlation with different regions. However, it seems that the stratigraphic range of several dinocyts will be different in southwestern Europe. An example is the range top of *Mancodinium semitabulatum* in the Lusitanian Basin which is in the lowermost Aalenian (Bifidatum Subzone), whereas in northwest Europe its consistent range top extend to the Bajocian (Correia et al., 2019).

5 Conclusions

This study presents a synthesis of all the data collected in the Iberian Peninsula over the last decades on ammonoids, brachiopods, foraminifera, ostracods, palynomorphs and microfacies of the Early Jurassic-Middle Jurassic boundary. To achieve this goal, a detailed (zone and subzone) biostratigraphic analysis of the defined scales of the different fossil groups has been carried out, together with a detailed petrographic description of the different microfacies identified in the Iberian Cordillera.

In the Iberian Cordillera, the Fuentelsaz microfacies fossil content is characterized by abundant bivalves (*Bositra* filaments) throughout the section, and a progressive increase of sponge spicules. Gastropods and bryozoans appear only in the lower part of the section. The microfacies showed that foraminifera tests, echinoderms plates ostracods, serpulids and brachiopods are always present with a low percentage, though in the lower part of the section they are more abundant.

Regarding ammonoids, the zonal scales defined in the Iberian and Betic Cordilleras, and the Lusitanian and Basque-Cantabrian basins of the Iberian Peninsula were reviewed. These scales have been compared with the Standard Zonation established for the provinces of northwestern Europe and the Mediterranean. Furthermore, they have been calibrated with regional scales based on brachiopods, foraminifera, ostracods, and palynomorphs.

The following useful elements have been highlighted to establish correlations between the Iberian area and other peri-Iberian basins:

- The ammonoid biostratigraphic scale, based on the succession of Grammoceratid and Graphoceratid species in the Iberian Peninsula, guarantees a high degree of resolution and precise correlation with the rest of the northwestern European basins. It can also be calibrated with the scale established in the Betic Cordillera, based on Mediterranean elements such as the Hammatoceratids, allowing correlations across the entire Tethys.
- Regarding brachiopods, differentiating between assemblages involves a difficult correlation between different basins. The only element of correlation is *Homoeorhynchia cynocephala*, a species widely distributed in the western Tethys, recognized in the Iberian Cordillera and Basque-Cantabrian basin, and occasionally in the Lusitanian basin.
- Concerning the foraminiferal zonal scale, the Astacolus dorbignyi Zone was established, recognized in other European basins, although with a broader range (upper Toarcian-uppermost Aalenian). However, the Lenticulina quenstedti Zone was also defined in the Basque-Cantabrian Basin, where it begins at the base of the Bradfordensis Zone. This zone has also been recognized in the Iberian Cordillera and the Lusitanian Basin, confirming its validity at the scale of the Iberian Plate.
- The ostracod assemblages of the Fuentelsaz section are taxonomically similar to those of northwestern Europe, composed of different species of Praeschuleridea and present similar stratigraphic ranges. However, it is worth noting that to date, the zonal index species *Aphelocythere kuhni* (Ohmert) is not found in this section. However, *Kinkelinella fischeri* (Malz) is one of the most characteristic species of this area.
- Regarding palynomorphs, the presence of assemblages composed of wide stratigraphic ranges taxa, plus its low diversity, make correlation with different regions difficult. However, it seems that the stratigraphic range of several dinocysts is different from that of southwestern Europe. An example is the range top of *Mancodinium semitabulatum* in the Lusitanian Basin, which appears in the lowermost Aalenian (Bifidatum Subzone), while in northwestern Europe it extends into the Bajocian.
- In the Iberian Cordillera, the Fuentelsaz microfacies fossil content is characterized by abundant bivalves (*Bositra* filaments) throughout the section, and a progressive increase of sponge spicules. Gastropods and bryozoans appear only in the lower part of the section. The microfacies showed that foraminifera tests, echinoderms plates ostracods, serpulids and brachiopods are always present with a low percentage, though in the lower part of the section they are more abundant.

The data presented in this paper reflect the most up-to-date information on the zonation of different fossil groups during the Early/Middle Jurassic transition in the Iberian Peninsula. Their comparison with the Ammonoid Zones highlights their suitability as correlating indicators between different peri-Iberian basins.

Acknowledgements The data from Iberian Cordillera and Basque-Cantabrian Basin are the result of several years of work obtained by a multidisciplinary team led by Professor Antonio Goy to whom we would like to express our deepest gratitude and recognition for the effort and dedication he has had with us all these years. This work is a contribution of the following research groups and projects: UCM 910431, Procesos Bióticos Mesozoicos (PBM), EMMI Research Group (RNM 0178 Junta de Andalucia, Spain), Portuguese funds of Fundação para a Ciência e a Tecnologia in the frame of UIDB/00073/2025 (https://doi.org/https://doi.org/10.54499/UIDB/00073/2020) and the UIDP/00073/2025 (https://doi.org/https://doi.org/10.54499/UIDP/00073/2020) projects of the I & D unit of Geosciences Center (CGEO). We gratefully acknowledge the anonymous reviewers for their thorough reviews and supportive comments.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. Fundação para a Ciencia e a Tecnologia (PT), UIDB/00073/2025, Maria Helena Henriques, projects of the I & D unit of Geosciences Center (CGEO). UIDP/00073/2025, José Sandoval.

Data availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Andrade, B. (2006). Los braquiópodos del tránsito Jurásico Inferior-Jurásico Medio de la Cuenca Lusitánica (Portugal). *Coloquios De Paleontología, 56*, 5–194.

Andrade, B., Duarte, L. V., García Joral, F., Goy, A., & Henriques, M. H. (2016). Palaeobiogeographic patterns of the brachiopod assemblages of the Iberian Subplate during the Late Toarcian-Early Aalenian (Jurassic). *Palaeogeography, Palaeoclimatology, Palaeoecology, 442*, 12–22. https://doi.org/10.1016/j.palaeo.2015.10.053

Arias, C., García-Frank, A., Canales, M. L., & Ureta, S. (2009). Ostracods from the Global Stratotype Section for the base of the Aalenian stage, Jurassic, at Fuentelsaz section (Cordillera Iberica, Spain). *Rivista Italiana di Paleontologia e Stratigrafia, 115*(2), 209–232. https://doi.org/10.13130/2039-4942/6380

Baeza Carratalá, J. F., García Joral, F., & Tent-Manclus, J. E. (2011). Biostratigraphy and paleobiogeographic affinities of the Jurassic brachiopod assemblages from Sierra Espuña (Maláguide Complex, Internal Betic Zones, Spain). *Journal of Iberian Geology, 37*, 137–151. https://doi.org/10.5209/rev_JIGE.2011.v37.n2.3

Baeza-Carratalá, J. F. (2013). Diversity patterns of Early Jurassic brachiopod assemblages from the westernmost Tethys (Eastern Subbetic). *Palaeogeography, Palaeoclimatology, Palaeoecology, 381*, 76–91. https://doi.org/10.1016/j.palaeo.2013.04.017

Baeza-Carratalá, J. F., García Joral, F., & Sandoval, J. (2014). Bajocian-Early Bathonian (Jurassic) brachiopods from the Subbetic domain (Betic Cordillera, SE Spain): taxonomy and palaeobiogeographic implications. *Neues Jahrbuch Für Geologie und Paläontologie (Abh.), 274*(1), 1–24. https://doi.org/10.1127/njgpa/2014/0440

Baeza-Carratalá, J. F., Vörös, A., Dulai, A., & Tent-Manclús, J. E. (2011). Brachiopod assemblages from the Early-Middle Jurassic transition in the Eastern Subbetic (SE Spain): Systematic and palaeobiogeographic implications and palaeoenvironmental significance. *Neues Jahrbuch fur Geologie und Palaontologie - Abhandlungen, 262*(2), 171–197.

Barbieri, F. (1964). Micropaleontologia del Lias e Dogger del pozo Ragusa 1 (Sicilia). *Rivista Italiana di Paleontologia e Stratigrafia, 70*(4), 709–830.

Barrón, E., Ureta, S., Goy, A., & Lassaletta, L. (2010). Palynology of the Toarcian-Aalenian Global Boundary Stratotype Section and Point (GSSP) at Fuentelsaz (Lower–Middle Jurassic, Iberian Range, Spain). *Review of Palaeobotany and Palynology, 162*, 11–28. https://doi.org/10.1016/j.revpalbo.2010.04.003

Bartenstein, H., & Brand, E. (1937). Mikro-paläontologische Untersuchungen zur Stratigraphie des nordwest-deutschen Lias und Doggers. *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft, 439*, 1–224.

Batten, D. J., & Dutta, R. J. (1997). Ultrastructure of exine of gymnospermous pollen grains from Jurassic and basal Cretaceous deposits in Northwest Europe and implications for botanical relationships. *Review of Palaeobotany and Palynology, 99*(1), 25–54. https://doi.org/10.1016/S0034-6667(97)00036-5

Bejjaji, Z., Chakiri, S., Reolid, M., & Boutakiout, M. (2010). Foraminiferal biostratigraphy of the Toarcian deposits (Lower Jurassic) from the Middle Atlas (Morocco). Comparison with western Tethyan areas. *Journal of African Earth Sciences, 57*(1–2), 154–162. https://doi.org/10.1016/j.jafrearsci.2009.08.002

Boutakiout, M. (1990). Les foraminifères du Jurassique des Rides sud-rifaines et des régions voisines (Maroc). *Documents des Laboratoires De Géologie De Lyon, 112*, 216.

Canales, M. L., Ureta, M. S., Hernández, L. & García-Frank, A. (2013). Bioestratigrafía comparada y bioeventos (ammonoideos y foraminíferos) en Hontoria del Pinar (Noroeste de la Cordillera Ibérica). In: Álvarez-Vázquez, C. & López-Rodríguez, I. (Eds.): *Libro de Resúmenes de las XXIX Jornadas de la Sociedad Española de Paleontología y Simposio del Proyecto PICG 596*, pp. 139–140.

Canales, M. L. (2001). Los foraminíferos del Aaleniense (Jurásico Medio) en la Cuenca Vasco-Cantábrica (N de España). *Revista Española De Micropaleontología, 33*, 253–438.

Canales, M. L., García-Baquero, G., Henriques, M. H., & Figueiredo, V. L. (2014). Palaeoecological distribution pattern of Early-Middle Jurassic benthic foraminifera in the Lusitanian Basin (Portugal) based on multivariate analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology, 410*, 14–26. https://doi.org/10.1016/j.palaeo.2014.05.007

Canales, M. L., & Henriques, M. H. (2008). Foraminifera from the Aalenian and Bajocian GSSP (Middle Jurassic) of Murtinheira section (Cabo Mondego, West Portugal): Biostratigraphy and paleoenvironmental implications. *Marine Micropaleontology, 67*, 155–179. https://doi.org/10.1016/j.marmicro.2008.01.003

Canales, M. L., & Herrero, C. (2000). Asociaciones de foraminíferos del Toarciense superior y Aaleniense en la sección de Moyuela (Zaragoza, España). *Revista Española De Micropaleontología, 32*(3), 301–317.

Chandler, R., & Callomon, J. H. (2009). The Inferior Oolite at Coombe Quarry, near Mapperton, Dorset, and a new Middle Jurassic ammonite faunal horizon, Aa-3b, Leioceras comptocostosum n. biosp. in the Scissum Zone of the Lower Aalenian. In *Proceedings of the Dorset Natural History and Archaeological Society*, *130*, 99–132.

Copestake, P. & Johnson, B. (1984). Lower Jurassic (Hettangian-Toarcian) Foraminifera from the Mochras Borehole, North Wales (UK) and their application to a worldwide biozonation. In: Oertli, H. J. (Ed.): *Benthos' 83, 2nd International Symposium on Benthic Foraminifera* (Pau, 1983). Elf Aquitaine, Esso REP and Total CFP, Pau and Bordeaux, pp. 83–184.

Correia, V. F., Riding, J. B., Henriques, M. H., Fernandes, P., Pereira, Z., & Wiggan, N. J. (2019). The Middle Jurassic palynostratigraphy of the northern Lusitanian Basin. *Portugal, Newsletters on Stratigraphy, 52*(1), 73–96.

Cresta, S., Goy, A., Ureta, S., Arias, C., Barrón, E., Bernad, J., Canales, M. L., García-Joral, F., García-Romero, E., Gialanella, P. R., Gómez, J. J., González, J. A., Herrero, G., Martínez, G., Osete, M. L., Perilli, N., & Villalaín, J. J. (2001). The Global Boundary Stratotype Section and Point (GSSP) of the Toarcian-Aalenian boundary (Lower-Middle Jurassic). *Episodes, 24*(3), 166–175.

Davis, M. B. (2000). Palynology after Y2K-Understanding the source area of pollen in sediments. *Annual Review of Earth and Planetary Sciences, 28*, 1–18. https://doi.org/10.1146/annurev.earth.28.1.1

Dera, G., Pellenard, P., Neige, P., Deconinck, J.-F., Pucéat, E., & Dommergues, J. L. (2009). Distribution of clay minerals in Early Jurassic Peritethyan seas: Palaeoclimatic significance inferred from multiproxy comparisons. *Palaeogeography, Palaeoclimatology, Palaeoecology, 271*, 39–51. https://doi.org/10.1016/j.palaeo.2008.09.010

Dietze, V., Gräbenstein, S., Franz, M., Schweigert, G., & Wetzel, A. (2021). The middle jurassic opalinuston formation (Aalenian, Opalinum Zone) at its type locality near Bad Boll and adjacent outcrops (Swabian Alb, SW Germany). *Palaeodiversity*, *14*(1), 15–113. https://doi.org/10.18476/pale.v14.a3.

Elmi, S., Goy, A., Mouterde, R., Rivas, P., & Rocha, R. (1989). Correlaciones bioestratigráficas en el Toarciense de la Península Ibérica. *Cuadernos De Geología Ibérica, 13*, 265–277.

Exton, J., Gradstein, F. M., & Westermann, G. E. G. (1984). Early Jurassic stratigraphy and micropaleontology of the Grand Banks and Portugal. *Geological Association of Canada Special Paper, 27*, 13–30.

Fernández-López, S., Henriques, M. H., Mouterde, R., Rocha, R. & Sadki, D. (1988). Le Bajocien inférieur du Cap Mondego (Portugal). Essai de biozonation. In: Rocha, R.B. & Soares, A.F. (eds.), *Proceeding 2nd International Symposium on Jurassic Stratigraphy. INIC* Lisboa, pp. 301–314.

Fernández-López, S., & Suárez-Vega, L. C. (1980). Estudio biostratigráfico (Ammonoidea) del Aaleniense y Bajociense en Asturias. *Estudios Geológicos, 35*, 231–239.

Figueiredo, V., Canales, M. L., & Henriques, M. H. (2014). Foraminifera of the Toarcian-Aalenian boundary from the Lusitanian Basin (Portugal): a paleoecological analysis. *Journal of Iberian Geology, 40*(3), 431.

Figueiredo, V. L., Henriques, M. H., & Canales, M. L. (2010). Foraminíferos bentónicos da passagem Jurássico Inferior-Médio do sector central da Bacia Lusitânica: O perfil de Zambujal de Alcaria. *Boletim De Geociências Da Petrobras, 19*(1/2), 207–231.

García Joral, F. & Goy, A. (2000). Stratigraphic distribution of Toarcian brachiopods from the Iberian Range (Spain) and its relation to depositional sequences. *In*: Advances in Jurassic Research 2000. Proceedings of the Fifth International Symposium on the Jurassic System. *GeoResearch. Forum*, *6*, 381–386.

García Joral, F. & Goy, A. (2009b). Diferenciación paleobiogeográfica de los braquiópodos del Toarciense Superior (Jurásico) en los bordes Norte y Este de la Meseta Ibérica. In: *Comunicaciones de las XXV Jornadas de la Sociedad Española de Paleontología* (P. Palmqvist & J.A. Pérez-Claros, Coords.), pp. 302–305.

García Joral, F. & Goy, A. (2010). Biozonas de Rhynchonellida (Brachiopoda) del Toarciense de las Cordilleras Ibérica y Cantábrica (España). *V Congreso del Jurásico de España*. Museo del Jurásico de Asturias, Colunga, pp. 65–72.

García Joral, F., & Goy, A. (1994). The associations of Brachiopods from the Toarcian-Aalenian transition in the Fuentelsaz section (Iberian Range, Spain). *Geobios, 27*, 223–228. https://doi.org/10.1016/S0016-6995(94)80141-X

García Joral, F., & Goy, A. (2009a). Toarcian (Lower Jurassic) brachiopods in Asturias (Northern Spain): Stratigraphic distribution, critical events and palaeobiogeography. *Geobios, 42*(3), 255–264. https://doi.org/10.1016/j.geobios.2008.10.007

García Joral, F., Goy, A., & Ureta, M. S. (1990). Las sucesiones de braquiópodos en el tránsito Lías-Dogger en la Cordillera Ibérica. *Cuadernos De Geología Ibérica, 14*, 55–65.

García-Frank, A., Perilli, N., & Ureta, S. (2010). Microfacies and Nannofacies Analysis of Fine-Carbonate Fraction at the GSSP Aalenian Stage of Fuentelsaz Section (Iberian Range, Spain): Implications for the palaeoenvironmental Evolution. *Earth Sci Frontier, 17*, 17–18.

García-Gómez, R., Jiménez Jiménez, A. P., Linares, A., Rivas, P., & Sandoval, J. (1994). The Toarcian-Aalenian boundary in the Betic Cordillera (Southern Spain). *Geobios, 17*, 211–222. https://doi.org/10.1016/S0016-6995(94)80140-1

Gómez, J. J., Canales, M. L., Ureta, S., & Goy, A. (2009). Paleoclimatic and biotic changes during the Aalenian (Middle Jurassic) at the southern Laurasia Seaway (Basque–Cantabrian Basin, northern Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology, 275*, 14–27. https://doi.org/10.1016/j.palaeo.2009.01.009

Gómez, J. J., Comas-Rengifo, M. J., & Goy, A. (2003). Las unidades litoestratigráficas del Jurásico Inferior de las cordilleras Ibérica y Costero Catalana. *Revista Sociedad Geológica De España, 16*(3–4), 227–237.

Gómez, J. J., & Fernández-López, S. (2004). Las unidades litoestratigráficas del Jurásico medio de la Cordillera Ibérica. *Geogaceta, 35*, 91–94.

Gómez, J. J., & Goy, A. (2005). Late Triassic and Early Jurassic palaeogeographic evolution and depositional cycles of the Western Tethys Iberian platform system (Eastern Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology, 222*, 77–94. https://doi.org/10.1016/j.palaeo.2005.03.010

Goy, A., Comas-Rengifo, M. J. & García Joral, F. (1984). The Liassic Brachiopods of the Iberian Range (Spain): Stratigraphic Distribution and Biozonation. In: Michelsen & O., Zeiss, A. (Eds.), *International Symposium on Jurassic Stratigraphy. Erlangen, September 1–8, 1984. Volume 1*. Geological Survey of Denmark, Copenhagen, pp. 227–250.

Goy, A., Jiménez, A., Martínez, G. & Rivas, R. (1988). Difficulties in correlating the Toarcian ammonite sucesión of the Iberian and Betics Cordilleras. In: Rocha, R. & Soares, A. (Eds.), *2nd International Symposium on Jurassic Stratigraphy*, *I.N.I.C.,* Lisboa, pp. 155–178.

Goy, A. & Ureta, S. (1994). Bioestratigrafia del Aaleniense en el sector occidental de la Cuenca Vasco-Cantábrica. *Comunicaciones de las X Jornadas de Paleontologia*, pp. 102–105.

Goy, A., Comas Rengifo, M. J., Gómez, J. J., Herrero, C., Suárez-Vega, L. C. & Ureta, S. (2010). Biohorizontes de ammonoideos del Toarciense en Asturias. In: Ruiz de Omeñaca, J. J., Piñuela, L & García Ramos J. C. (eds.). *Comunicaciones V Congreso Jurásico de España,* pp. 94–102.

Goy, A. (1985). Jurassique des Ibérides. *Strata, 2*, 32–56.

Goy, A., Gómez, J. J., & Yébenes, A. (1976). El Jurásico de la Rama Castellana de la Cordillera Ibérica (mitad Norte). *I. Unidades Litoestratigráficas. Estudios Geológicos, 32*, 391–423.

Goy, A., & Martínez, G. (1990). Biozonación del Toarciense en el área de La Almunia de Doña Godina-Ricla (Sector Central de la Cordillera Ibérica). *Cuadernos De Geología Ibérica, 14*(II), 11–53.

Goy, A., Martínez, G., & Ureta, S. (2006). Ammonoidea Toarcian biohorizon in the Basque-Cantabrian Basin (N Spain): A correlation betwen the Iberian Range and the Mediterranean province standard scale. *Volumina Jurassica, 4*, 166–167.

Goy, A., & Ureta, M. S. (1981). Bioestratigrafía del Aaleniense en Préjano-Muro de Aguas (Logroño). *Cuadernos De Geología Universidad De Granada, 10*, 107–119.

Goy, A., & Ureta, S. (1987). Leioceratinae (Ammonitina) del Aaleniense inferior de Fuentelsaz (Cordillera Ibérica, España). *Bolletino della Società Paleontologica Italiana, 4*, 213–236.

Goy, A., & Ureta, S. (1990). El Aaleniense en la Cordillera Ibérica. *Les Cahiers de l'Université Catholique de Lyon. Série Sciences, 4*, 73–87.

Goy, A., Ureta, S., Arias, C., Canales, M. L., García-Joral, F., Herrero, C., Martínez, G., & Perilli, N. (1994). The Fuentelsaz section (Iberian Range, Spain), a possible Stratotype for the base of the Aalenian Stage. *Miscellanea Del Servizio Geologico Nazionale, 5*, 1–31.

Gradstein, F. M. (1977). Biostratigraphy and biogeography of Jurassic Grand Banks foraminifera. In: Schafer, G. T. H. & Bernard, R. P. (eds.): *1st International Symposium on Benthonic Foraminifera of Continental Margins. Part B: Paleoecology and Biostratigraphy*. (Halifax, 1975). Maritime Sediments, Special Publication, *1*, 557–583.

Gradstein, F. M. (1978). Jurassic Grand Banks Foraminifera. *Journal of Foraminiferal Research, 8*, 97–109.

Guterres, H. C. (2010). *Foraminiferos do limite Jurássico Inferior-Médio do Sector Norte da Bacia Lusitânica: O perfil de Maria Pares (Rabaçal).* Tese de Mestrado, Departamento de Ciências da Terra, Faculdade de Ciência e Tecnologia da Universidade de Coimbra, 76 pp. (unpublished).

Henriques, M. H. (1992). *Biostratigrafia e paleontologia (Ammonoidea) do Aaleniano em Portugal (Sector setentrional da Bacia Lusitaniana)*. Tese doutoramento, Centro Geociências Univ. Coimbra, Inédita, pp. 1–301, fig. 1.1–2.32, est. 1–7.

Henriques, M. H. (1995). Les faunes d'ammonites de l'Aalénien Portugais: composition et implications paleobiogéographiques. In: Gayet M. & Courtinat B. (Eds.), *First European Paleontological Congress*, Lyon 1993, Geobios, Lyon, 28, Suppl. 1 (M. S. nº 18), pp. 229–235. https://doi.org/10.1016/S0016-6995(95)80169-3

Henriques, M. H. (2000a). Biostratigraphie (Ammonoidea) du passage Lias-Dogger dans le Bassin Lusitanien: La coupe de S. Gião. *Strata, 10*, 31–35.

Henriques, M. H. (2000b). Aalenian of the Zambujal de Alcaria Section (Central Lusitanian Basin, Portugal). *GeoResearch Forum, 6*, 85–94.

Henriques, M. H., & Canales, M. L. (2013). Ammonite-benthic foraminifera biostratigraphy across the Lower-Middle Jurassic transition of São Gião section (Lusitanian Basin, Portugal). *Geobios, 46*, 395–408. https://doi.org/10.1016/j.geobios.2013.06.002

Henriques, M. H., Canales, M. L., Silva, S. C., & Figueiredo, V. (2016). Integrated biostratigraphy (Ammonoidea, Foraminiferida) of the Aalenian of the Lusitanian Basin (Portugal): A Synthesis. *Episodes, 39*(3), 482–490.

Henriques, M. H., Linares, A., Sandoval, J., & Ureta, M. S. (1996). The Aalenian in the Iberia (Betic, Lusitanian and Iberian Basins). *GeoResearch Forum, 1–2*, 139–150.

Hernández, L. (2015). *Foraminíferos da passage Aaleniano-Bajociano no Sector Setentrional da Cordilheira Ibérica – O perfil de Talveila*. Tese de Mestrado, Departamento de Ciências da Terra, Faculdade de Ciências e Tecnologia da Universidade de Coimbra, 113 pp. (unpublished).

Hernández, L., Canales, M. L., & Henriques, M. H. (2018). Response of benthic foraminiferal assemblages to contrasting environments during the Aalenian-Bajocian in the Iberia: A case study from the Talveila section (Iberian Range) and Murtinheira section (Lusitanian Basin). *Journal of Iberian Geology, 44*, 447–478. https://doi.org/10.1007/s41513-018-0067-1

Herrero, C., & Canales, M. L. (1997). Diversidad en los foraminíferos del tránsito Toarciense/Aaleniense en la sección de Fuentelsaz (Cordillera Ibérica). *Revista Española De Paleontología, 12*, 233–242. https://doi.org/10.7203/sjp.24022

Knitter, H., & Riegraf, W. (1984). Biostratigraphie (Cephalopoden, Ostracoden) des Oberen Toarcium von Blumberg-Achdorf/Wutach und Weilheim/Teck (Baden-Württemberg). *Jahreshefte des geologischen Landesamtes in Baden-Württemberg, 26*, 57–97.

Linares, A., Ureta, M. S., & Sandoval, J. (1988). Comparison between the Aalenian ammonite associations from the Betic and Iberian cordilleras: elements of correlation. In: Rocha, R. B. & Soares, A. F. (eds.), *2nd International Symposium on Jurassic Stratigraphy*, I.N.I.C, Lisboa, pp. 193–208.

Linares, A., & Sandoval, J. (1993). El Aaleniense de la Cordillera Bética (Sur de España). Análisis bioestratigráfico y caracterización paleobiogeográfica. *Revista De La Sociedad Geológica De España, 6*, 177–206.

Martínez, G. (1992). *Hammatoceratinae (Ammonitina) del Toarciense Superior y Aaleniense en la Cordillera Ibérica*. Colección Tesis Doctorales, 374/92, UCM, Madrid, 331 pp.

Martínez, G., Sandoval, J., Ureta, S., & Goy, A. (2015). *Geczyceras* (Hammatoceratidae, Ammonoidea) in the western Tethys: Biostratigraphic analysis between Northwest European Province (Iberian Range) and Mediterranean Province (Betic Cordillera). *Hantkeniana, 10*, 13–28.

Mira, F. J. (1986). *Foraminíferos del Lías margoso de las Cordilleras Béticas. Zona Subbética*. Tesis Doctoral. Universidad de Granada, 242 pp. (unpublished).

Ohmert, W. (2004). Ammoniten-Faunen im tiefen Unter-Bajocium des Reutlinger Gebiets (mittlere Schwäbische Alb) [mit einem Beitrag zur Ostracoden-Stratigraphie]. *Jahreshefte des Landesamtes Für Geologie, Rohstoffe und Bergbau in Baden-Württemberg, 40*, 9–141.

Peyrot, D., Barrón, E., Comas-Rengifo, M. J., Thouand, E., & Tafforeau, P. (2007). A confocal laser scanning and conventional wide field light microscopy study of *Classopollis* from the Toarcian-Aalenian of the Fuentelsaz section (Spain). *Grana, 46*, 217–226. https://doi.org/10.1080/00173130701782845

Quesada, S., Robles, S., & Rosales, I. (2005). Depositional architecture and transgressive/regressive cycles within Liassic backstepping carbonate ramps in the Basque-Cantabrian basin, northern Spain. *Journal of the Geological Society, 162*, 531–548. https://doi.org/10.1144/0016-764903-041

Romero, S. &, Canales M. L. (2022). Estudio de los foraminíferos bentónicos del Suborden Lagenina del tránsito Jurásico Inferior-Medio de la sección de Cerro Méndez (Cordilleras Béticas, S de España). In: Blanco, F., Blanco-Moreno, C., Buscalioni, A. D., de la Cita, L., Llandres, M., Martín-Abad, H., Marugán-Lobón, J., Monleón, M. A.,Navalón, G., Nebreda, S. M., Prieto, I. & San Román, C. (eds.): *Libro de Resúmenes XXXVII Jornadas de Paleontología SEP/V Congreso Ibérico de Paleontología.* Cuenca, p. 169.

Sandoval, J., Bill, M. M., Aguado, R., ÓDogherty, L., Rivas, P., Morard, A., & Guex, J. (2012a). The Toarcian in the Subbetic basin (southern Spain): Bio-events (ammonite and calcareous nannofossils) and carbon-isotope stratigraphy. *Palaeogeography, Palaeoclimatology, Palaeoecology, 342–343*, 40–63.

Sandoval, J., Henriques, M. H., Chandler, R. B., & Ureta, M. S. (2012b). Latest Toarcian-earliest Bajocian (Jurassic) Grammoceratinae (Hildoceratidae, Ammonitina) of the western Tethys: Their palaeobiogeographic and phylogenetic significance. *Geobios, 45*, 109119. https://doi.org/10.1016/j.geobios.2011.11.001

Sandoval, J., Henriques, M. H., Ureta, M. S., Goy, A., & Rivas, P. (2001). The Lias/Dogger boundary in Iberia: Betic and Iberian cordilleras and Lusitanian basin. *Bulletin Societé Géologique France, 172*, 387–395. https://doi.org/10.2113/172.4.387

Sandoval, J., Martínez, G., & Ureta, S. (2011). Upper Toarcian-lower Bajocian (Jurassic) Hammatoceratoidea (Ammonitina) of the Betic Cordillera (southern Spain): Biostratigraphy and palaeobiogeography. *Bulletin Societé Géologique France, 182*, 45–58. https://doi.org/10.2113/gssgfbull.182.3.241

Sandoval, J., Martínez, G., & Ureta, S. (2015). Toarcian-Aalenian Erycitinae, Ammonitida, of the westernmost Tethys (southern Spain): Taxonomical and phylogenetical implications. *Palaeontographica Abt A, 304*, 77–119. https://doi.org/10.1127/pala/304/2015/77

Sandoval, J., Martínez, G., & Ureta, S. (2020). Hammatoceratidae (Ammonitina) from the Upper Toarcian-Lowermost Bajocian (Jurassic) of the Betic Cordillera (Southern Spain). *Palaeontographica Abt A, 315*(1–4), 1–65. https://doi.org/10.1127/pala/2020/0092

Sandoval, J., O'Dogherty, L., Aguado, R., Bartolini, A., Bruchez, S., & Bill, M. (2008). Aalenian carbon isotope-stratigraphy: Calibration with ammonite, radiolarian and nannofossils events in the Western Tethys. *Palaeogeography, Palaeoclimatology, Palaeoecology, 267*, 115–137. https://doi.org/10.1016/j.palaeo.2008.06.013

Santos, A. A., Rodríguez-Barreiro, I., McLoughlin, S., Pons, D., Valenzuela-Ríos, I., & Díez, J. B. (2024). Plant colonization of isolated palaeoecosystems: Palynology of a Middle Jurassic extinct volcanic island (Camarena, Teruel, Eastern Spain) Palaeogeography. *Palaeoclimatology, Palaeoecology, 639*, 112081. https://doi.org/10.1016/j.palaeo.2024.112081

Schrank, E. (2003). Small acritarchs from the Upper Cretaceous: Taxonomy, biological affinities and palaeoecology. *Review of Palaeobotany and Palynology, 123*, 199–235.

Silva, S. C., Canales, M. L., Sandoval, J. & Henriques, M. H. (2015b). Benthic foraminiferal assemblages across the Aalenian-Bajocian (Middle Jurassic) in the Barranco de Agua Larga section (Betic Cordillera, Spain) – biostratigraphic considerations. In: *AAPG, European Regional Conference and Exhibition – Tethys-Atlantic Interaction Along the European-Iberian-African Plate Boundaries*, Lisbon, pp. 83–84.

Silva, S. (2020). *Foraminíferos da passagem Aaleniano-Bajociano na Península Ibérica.* Tese doutoramento, Centro Geociências Univ. Coimbra, Inédita, pp. 1–499.

Silva, S. C., Henriques, M. H., & Canales, M. L. (2015a). High resolution ammonite-benthic foraminiferal biostratigraphy across the Aalenian-Bajocian boundary in the Lusitanian Basin (Portugal). *Geological Journal, 50*(4), 477–496. https://doi.org/10.1002/gj.2556

Spicer, R. A. (1991). Plant taphonomic processes. In P. A. Allison & D. E. Briggs (Eds.), *Taphonomy releasing: The data locked in the fossil record* (pp. 71–113). Press.

Suárez-Vega, L. C. (1974). Estratigrafía del Jurásico en Asturias. *Cuadernos De Geología Ibérica, 3*, 1–304.

Traverse, A. (2007). *Paleopalynology* (2nd ed.). Dordrecht, The Netherlands: Springer.

Tyszka, J. (1999). Foraminiferal biozonation of the Early and Middle Jurassic in the Pieniny Klippen Belt (Carpathians). *Bulletin of the Polish Academy of Sciences, Earth Sciences, 47*(1), 27–46.

Ureta, M. S. (1985). *Bioestratigrafía y Paleontología (Ammonitina) del Aaleniense en el Sector Noroccidental de la Cordillera Ibérica*. Colección Tesis Doctorales, 1581/85, UCM, Madrid, 452 pp.

Wernli, R., & Septfontaine, M. (1971). Micropaléontologie comparée du Dogger du Jura meridional (France) et des Préalpes Médianes Plastiques romandes (Suisse). *Eclogae Geologicae Helvetiae, 64*(3), 437–458. https://doi.org/10.5169/seals-163989