Facies (2018) 64:4
https://doi.org/10.1007/s10347-017-0515-y

ORIGINAL ARTICLE

# An integrated analysis (microfacies and ichnology) of a shallow carbonate-platform succession: upper Aptian, Lower Cretaceous, Betic Cordillera

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Received: 7 June 2017 / Accepted: 4 November 2017 / Published online: 27 November 2017

## Abstract

Four lithofacies and 12 microfacies types recognized in an upper Aptian section in the Sierra de Bedmar-Jódar (Prebetic of Jaén) represent shallow lagoonal environments (marl and marly limestone) and sand bars that delimited the lagoon. The lagoonal facies reflect subtidal restricted water circulation with low energy. The sand bar facies (intertidal environment) have upper surfaces that show the effects of supratidal and subaerial conditions. The presence of early fractures in particular lithofacies shows the importance of local synsedimentary tectonics during sedimentation. *Thalassinoides*, ?*Arenicolites*, *Diplocraterion*, *Circolites*, *Gastrochaenolites* and *Trypanites* are recorded in different beds of this section, reflecting various states of substrate consistency, in the form of firmground, hardground, and rockground. Whereas firmground conditions were dominant in the lower part of the section, hardgrounds and rockgrounds are mainly present in the upper part of the section. Four types of shallowing-upward elementary sequence are recognized. All the sequences show at the base mudstone or wackestone microfacies representing a lagoonal environment, overlain by sand-bar grain-pack-stone facies corresponding to a bar bounding the lagoon. The factors that controlled their development were carbonate production and tectonic movements.

**Keywords** Prebetic · Aptian · Facies · Microfossils · Paleoenvironments · Substrate consistency · Sedimentary sequences

## Introduction

The Aptian stage (Early Cretaceous) records successive episodes of development, growth, and demise of shallow-water carbonate platforms in low-latitude settings. Also, during this stage there were major global episodes of environmental change, including enhanced volcanic activity (Larson 1991; Larson and Erba 1999; Méhay et al. 2009). This activity produced a marked increase in $pCO_2$ concentrations (Naafs et al. 2016) and probably favored a global warming, changes in the nutrient regime and the hydrologic cycle, and the depleted oxygen conditions related to Oceanic Anoxic Event 1a (OAE1a; e.g., Jenkyns 2010; Aguado et al. 2014; Erba et al. 2015). In addition, extensional tectonics related to rifting favored relative changes in sea level with local episodes of emergence. Collectively, these events resulted in a biotic crisis, the so-called mid-Aptian event. This event mostly affected the organisms living in neritic environments (Skelton and Gili 2012), and involved widespread episodes of shallow carbonate platform drowning (Weissert et al. 1998; Föllmi et al. 2006; Najarro et al. 2011; Castro et al. 2012, 2014; Masse and Ferneci-Masse 2013), leading to a maximum reduction in the extent of Aptian carbonate platforms (Skelton and Gili 2012). The upper Aptian recorded a progressive recovery of the neritic faunas and shallow carbonate platforms along with the successive development of progradational carbonate platforms, very well expressed in different basins such as the Prebetic in the Southern Iberian Palaeomargin (Vilas et al. 2004; Castro et al. 2008).

In the Prebetic Domain (Betic External Zones, Southern Spain; Fig. 1), the Aptian forms part of the major genetic unit K4 from Martín-Chivelet et al. (2002) and Vilas et al. (2004), interpreted as a second-order transgressive–regressive cycle divided into three minor depositional sequences, and bounded by tectonic events (Fig. 2). The marine

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sediments record a major transgression in the mid-Aptian, resulting in the marine connection between the Prebetic and the Iberian basins, which was coeval with the maximum reduction in extent of carbonate platforms in the Prebetic, and also with the global mid-Aptian event (Skelton and Gili 2012). The regressive part of the cycle records the progressive recovery and expansion of shallow carbonate platforms, strongly controlled in their stratigraphic architecture by the extensional tectonics related to North-Atlantic rifting (Martín-Chivelet et al. 2002; Vilas et al. 2004; Figs. 1 and 2).

Here a cyclic stratigraphic succession of shallow platform carbonates of early late Aptian age, which belongs to the so-called Prebetic of Jaén (westernmost part of the Prebetic platform; Nieto et al. 2012; Ruiz-Ortiz et al. 2014), is documented. This succession belongs to the regressive part of the second-order transgressive–regressive cycle (Martín-Chivelet et al. 2002; Vilas et al. 2004). The aim of this paper is to characterize the elementary sequences constituting the succession. To this end, a detailed integrated analysis of sedimentological features, microfacies, and trace fossils has been undertaken, in order to establish the detailed sedimentary evolution of the platform developed in the Sierra de Bedmar-Jódar Unit in the context of the Southern Iberian Palaeomargin (Fig. 1a, b).

## Geological setting

During the Aptian, the sedimentary basins of Iberia were influenced by the relative movement of the Eurasian and African plates. Seafloor spreading in the North Atlantic led to a phase of rapid anticlockwise rotation of Iberia relative to the Eurasian Plate (Ziegler 1988). In that geodynamic framework, extensional tectonics prevailed, also affecting the Southern Iberian Palaeomargin (García-Hernández et al. 1980; Martín-Chivelet et al. 2002) (Fig. 1b, c).

The Betic External Zones are made up of sedimentary successions deposited on the Southern Iberian Palaeomargin during the Mesozoic and Early Cenozoic (Fig. 1a–c). They are divided into the Subbetic and Prebetic, respectively representing the distal pelagic and the proximal shallow-marine platform settings adjacent to the Iberian continent. The Cretaceous outcrops of the Sierra de Bedmar-Jódar (Fig. 1c, d) correspond to the so-called Prebetic of Jaén, which represents the easternmost part of the Prebetic (Molina et al. 2012; Ruiz-Ortiz et al. 2014). This domain is at present separated from the main Prebetic outcrops of the Cazorla and Segura units to the west, by the dextral strike-slip fault of Tíscar (Sanz de Galdeano 2003; Fig. 1c). Nevertheless, the particular paleogeography of the area could also be significant for the interpretation of this outcrop (Ruiz-Ortiz et al. 2014).

The Sierra de Bedmar-Jódar stratigraphic succession (Fig. 1d) is composed of Cretaceous and Miocene carbonates. The Cretaceous is formed by a carbonate succession ranging from the Valanginian to the Cenomanian in age (Molina et al. 2012; Fig. 2). Between the Valanginian and Aptian there is a hiatus that embraces the Hauterivian and Barremian. The Valanginian is represented by hemipelagic marly limestone and marl with scarce siliciclastic interlayers (Los Villares Formation, Fig. 2). The Aptian and Albian are made up of a thick succession of limestone, marly limestone and marl, with well-developed lagoonal facies (Nieto et al. 2012; Molina et al. 2015), which belong to the Llopis and Seguilí formations (Aptian) and the Sácaras and Jumilla formations (Albian; Fig. 2). According to Ruiz-Ortiz et al. (2014), during the Aptian-Albian this sector of the Prebetic was a differentiated block (fault-block carbonate platform sensu Bosence et al. 1998), tilted to the northeast. This block was generated during the Atlantic rifting phase that affected the Southern Iberian Palaeomargin. The Aptian is represented by the carbonate platforms of the Llopis and Seguilí formations (Castro 1998; Castro et al. 2008), whereas in other sectors of the Prebetic this stage is recorded by a hemipelagic unit (Almadich Formation). This last stratigraphic unit has been interpreted as deposited during the maximum transgression of the Aptian second-order cycle (Castro et al. 2008). The studied section belongs to the Seguilí Formation (upper Aptian), which represents a vast carbonate platform that crops out across the entire Prebetic, from Jaén to Alicante (Figs. 1 and 2), with a very characteristic and marked cyclicity (e.g., Castro and Ruiz-Ortiz 1995).

## Materials and methods

A detailed logging bed-by-bed of the Bedmar-Jódar upper Aptian section (Fig. 3) was performed, including sampling of hard rock for thin-sections and marly beds for sieving.

A total of 35 thin-sections were studied, with a focus on microfacies as well as microfossil assemblages using a Leica M205 C stereoscopic microscope. Benthic foraminifera and calcareous algae were classified from thin-sections. In addition, six marly sieved samples were selected for the study of microfossils. The samples consisted of 0.5 kg of sediment that were soaked in tap water for 24 h. After disintegration, the rinsing procedure involved a column of standard stainless-steel sieves with mesh openings of 500, 200, 100, and 50 µm, and a gentle jet of water from the top. Residues were oven-dried at 40 °C. Specimens smaller than 100 µm are poorly preserved, and thus difficult to identify; they were not counted. Foraminifera, ostracods and algae were hand-picked with a hair paint-brush on a standard black picking grid-tray under stereoscopic microscopy. Gold-coated specimens of microfossils from sieved samples were analyzed

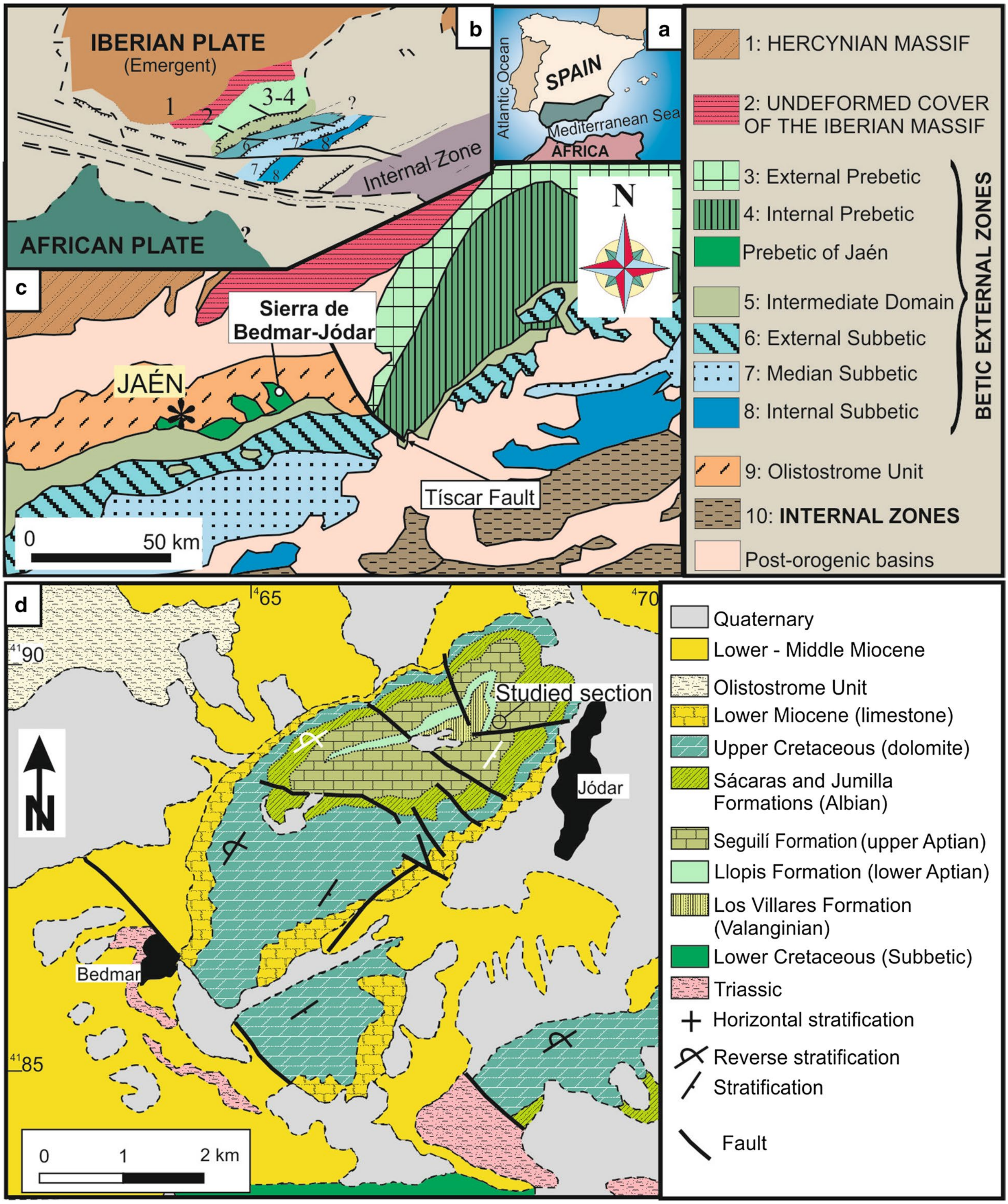

**Fig. 1** Geological setting of the Sierra de Bedmar-Jódar in the Betic External Zones. **a** Location of the Betics in southern Spain. **b** Paleogeographic reconstruction of the South Iberian margin for the Lower Cretaceous. **c** Location of the Sierra de Bedmar-Jódar in the Betic External Zones and relation with the Tíscar Fault. **d** Geological map of the Sierra de Bedmar-Jódar (modified from ITGE 1988, 1991) with the position of the studied section

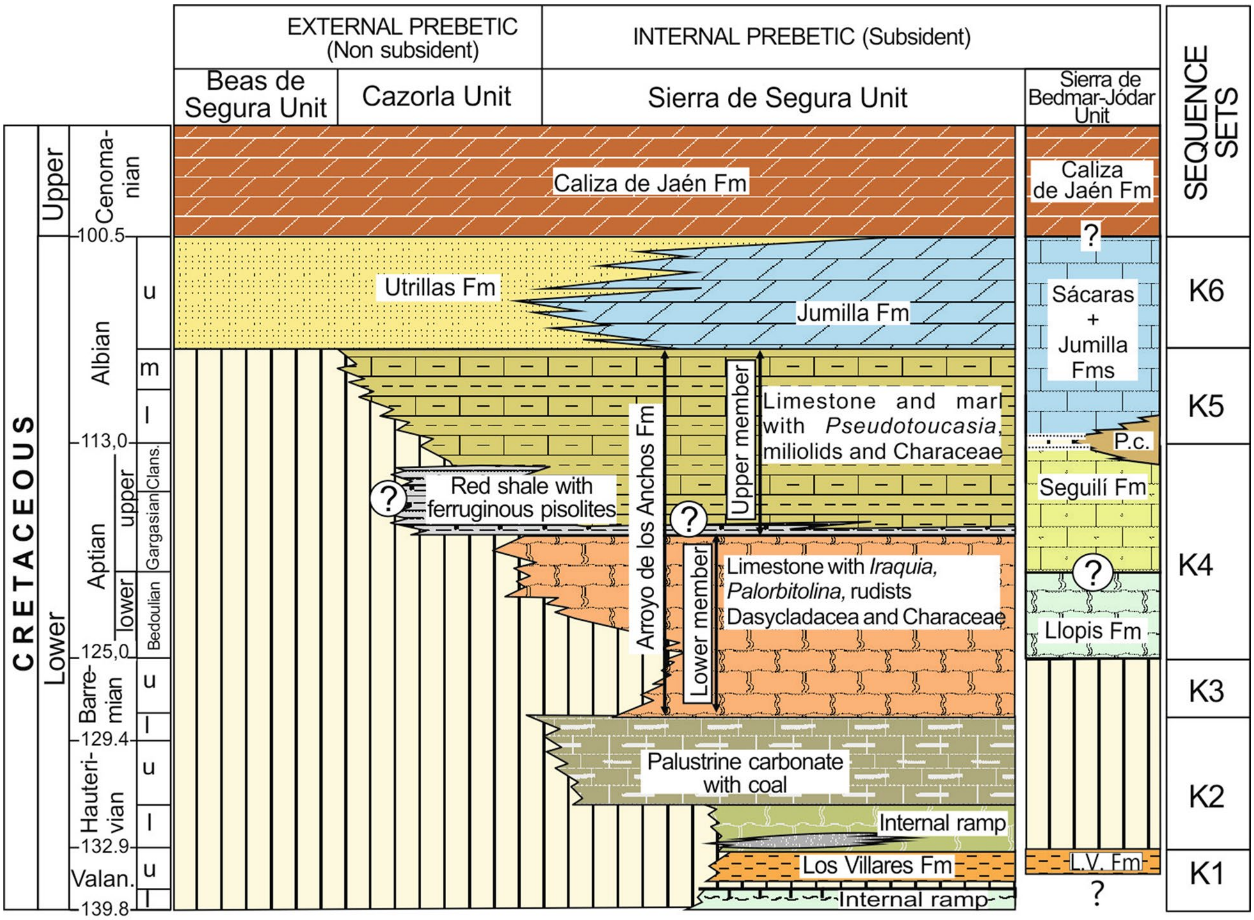

**Fig. 2** Chronostratigraphic chart of the Prebetic in the Cazorla and Segura region (slightly modified of García-Hernández et al. 2001) and correlation with the Sierra de Bedmar-Jódar and the sequences considered in the Prebetic (sensu Vilas et al. 2004). *P.c.* Palustrine carbonates

under scanning electron microscopy (SEM) and images were produced with a Merlin Carl Zeiss SEM in the Centro de Instrumentación Científico-Técnica of the Universidad de Jaén.

The analysis of trace fossils was based on outcrop observations of ichnological features including shape, configuration, orientation, length, width and diameter of the burrows, burrow margins, width between paired holes (when applicable) and sediment fill of the trace fossil. Moreover, burrow density was determined by counting the number of apertures present within 30 × 30 cm quadrat (0.09 $m^2$) sampling areas.

## Results

### Biostratigraphy

The studied section was dated through the presence of the foraminifera *Orbitolina* (*Mesorbitolina*) *texana* Roemer, found throughout the succession. This orbitolinid ranges from the upper Aptian to the base of upper Albian (e.g., Masse et al. 1992). The presence of other upper Aptian taxa (*Simplorbitolina* sp. and *Orbitolina* (*Mesorbitolina*) *subconcava* Schroeder) in beds located up-section of the studied interval permits the designation of the studied materials to Biostratigraphic Units 3 and 4, defined from the Prebetic of Alicante (Castro et al. 2001) and dated as the early-middle late Aptian interval.

### Facies and microfacies

The analysis of data obtained from outcrops and petrography led to the characterization of a total of 12 microfacies types belonging to four lithofacies associations (Table 1):

#### Lithofacies association 1: marl and marly limestone with mudstone texture

This lithofacies association contains common macrofossils, mostly represented by gastropods, rudists *Mathesia dardieri*

**Fig. 3** Stratigraphic section studied. The numbers in red represent the marls samples used to sieving

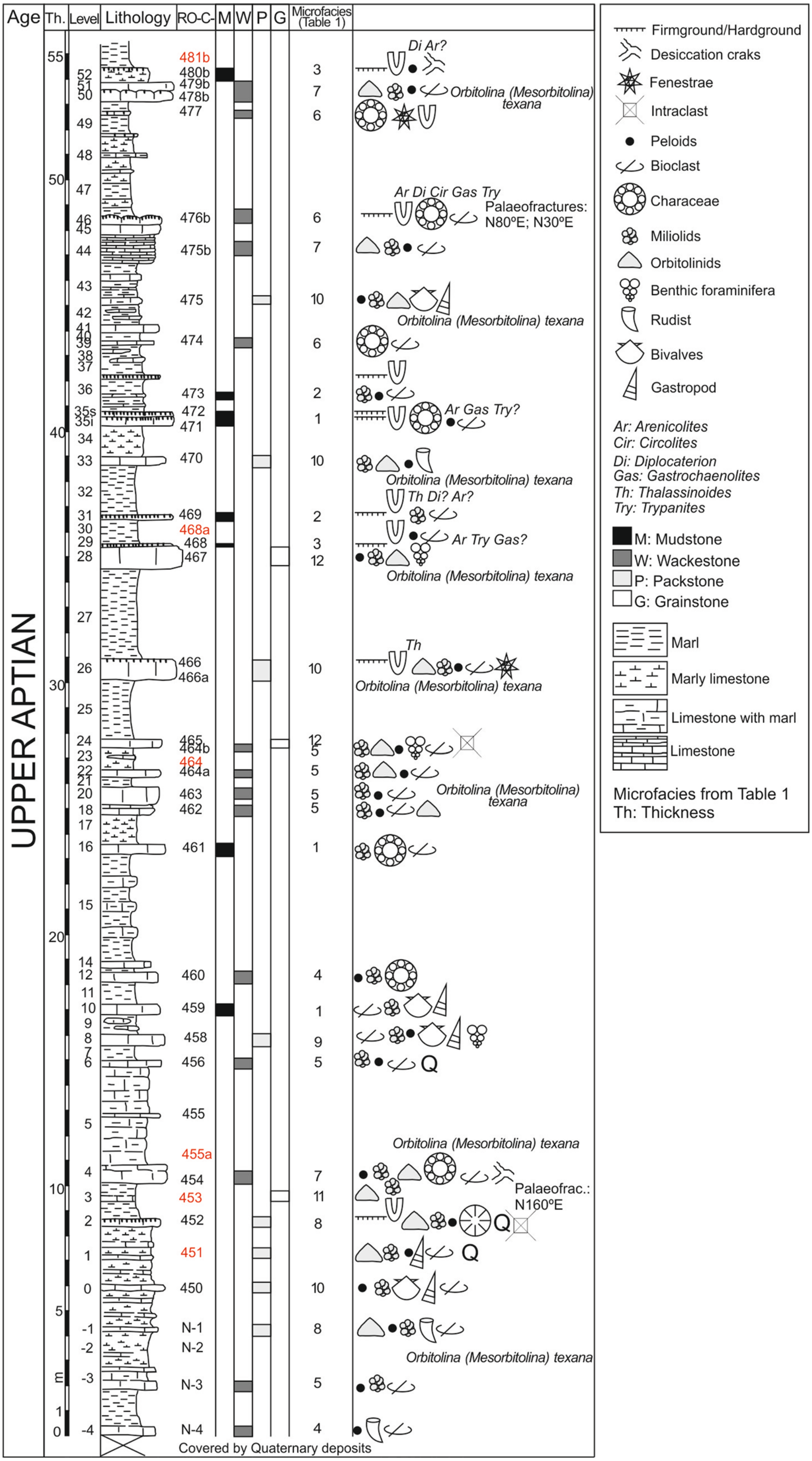

**Table 1** Types of lithofacies and microfacies and their features considered in the carbonates studied. It is also shown their relation with the sedimentary environment

| Lithofacies | | Microfacies | | Grains | Fossils | Other features | Environment |
|---|---|---|---|---|---|---|---|
| No. | | No. | | | | | |
| 1 | Marl and marly limestone with mudstone texture | 1 | Mudstone with bioclasts | Some peloids, (fecal pellets?) | Some miliolids, bivalves, gastropods, charophyta, serpulids | Micritic matrix, stained by FeO; lumpy texture. Sheet cracks | Inner ramp. Lagoon. Very low energy conditions |
| | | 2 | Mudstone with miliolids | Some peloids (fecal pellets?) | Miliolids, mollusc fragments | Micritic matrix, bioturbated | Inner ramp. Restricted subenvironment |
| | | 3 | Mudstone with peloids | Peloids (fecal pellets?) | Coral bioclasts and rudists | Micritic matrix, stained by FeO; partial dolomitization. Sheet cracks | Inner ramp. Lagoon. Very low energy conditions |
| 2 | Limestone with wackestone texture | 4 | Wackestone with peloids | Peloids (fecal pellets?), bioclasts | Miliolids, charophyta, rudists | Micritic matrix | Inner ramp. Lagoon. Very low energy conditions |
| | | 5 | Wackestone with miliolids | Peloids, bioclasts | Miliolids, orbitolinids, benthic foraminifera (*Cuneolina* sp., *Pseudotextularia* sp.) | Micritic matrix, in some samples, partially dolomitized | Inner ramp. Restricted subenvironment |
| | | 6 | Wackestone with charophyta | Bioclasts | Characea and clavatoracea | Micritic matrix bioturbated. Fenestrae. Partial dolomitization. | Inner ramp. Restricted subenvironment with continental influence |
| | | 7 | Wackestone with orbitolinids | Peloids, bioclasts | Orbitolinids, miliolids, serpulids, charophyta | Micritic matrix bioturbated. Sheet cracks. Very small scarce quartz grains. | Inner ramp. Restricted to open-marine subenvironments with high energy |
| 3 | Limestone with packstone texture | 8 | Packstone with orbitolinids | Peloids, bioclasts | Orbitolinids, miliolids, gastropods, rudists and other bivalves | Some small rounded quartz grains. Some orbitolinids have worn edges. Sheet cracks in some samples | |
| | | 9 | Packstone with bioclasts | Peloids, bioclasts | Miliolids, bivalves, gastropods, benthic foraminifera | Some fine quartz grains | |
| | | 10 | Packstone with peloids | Peloids, bioclasts | Orbitolinids, miliolids | Fenestrae | |
| 4 | Limestone with grainstone texture | 11 | Grainstone with orbitolinids | | Orbitolinids, miliolids | Some orbitolines have corroded edges | |
| | | 12 | Grainstone with peloids | Peloids, bioclasts | Orbitolinids, miliolids, benthic foraminifera | Contact between orbitolinids are stylolites | |

(Astre), and corals. Hardground surfaces are also present at the top of beds in this lithofacies (beds 29, 31, 35i, 35s, and 52; Fig. 3). Three microfacies types were identified (1–3 in Table 1):

- Microfacies 1: Mudstone with bioclasts (Table 1). It is characterized by a micritic matrix stained with iron oxide with lumps and peloids. Also mud cracks are present (Fig. 4a). Bioclasts are dominated by bivalve fragments, foraminifera (mainly *Quinqueloculina*, Figs. 5c, d, 6g, and secondarily *Ammobaculites,* Fig. 5g, *Trochammina,* Figs. 5i, 6b, and *Sabaudia,* Figs. 5e, 6d), charophyta (*Atopochara,* Figs. 5p–r, 6h–k), dasycladacean green algae (*Salpingoporella,* Fig. 5s), ostracods (*Paracypris,* Fig. 5m) and fragments of serpulids. Two hardground surfaces located in the upper part of the section have been recorded (beds 35i and 35s; Fig. 3).
- Microfacies 2: Mudstone with miliolids (Table 1). It is characterized by a micritic matrix with common trace fossils seen in cross section, peloids, foraminifera (*Quinqueloculina,* Figs. 5c, d, 6g, and less common *Sabaudia,* Figs. 5e, 6d, *Placopsilina*, *Ammobaculites*, Fig. 5h, *Trochammina,* Figs. 5i, 6b, *Lenticulina*, *Gyroidinoides*, *Astacolus,* Fig. 5k, *Flabellammina*, Fig. 5f, and fragments of orbitolinids, Figs. 5a, 6a) and ostracods (*Paracypris*, Fig. 5m). Other bioclasts are scarce, such as algal remains of *Cayeuxia* (Fig. 6l), oogonia and utricules of charophyta (*Atopochara*; Fig. 6h–k) or bivalves (Fig. 4b). This microfacies is in one case associated to a bed capped by a hardground surface with borings (bed 31; Fig. 3).
- Microfacies 3: Mudstone with peloids (Table 1, Fig. 4c). It is characterized by a micritic matrix stained by iron oxide and partially dolomitized. Among the grains, peloids are dominant and coral fragments are also present. Fenestrae are common in the uppermost part of the section. Microfauna are represented by *Cayeuxia* (Fig. 6l), fragments of orbitolinids and encrusting foraminifera such as *Placopsilina*. This microfacies is present in beds capped with hardground surfaces with borings (beds 29 and 52; Fig. 3).

## Lithofacies association 2: Limestone with wackestone texture

They consist of beds locally having mud cracks and locally with rudists (*Mathesia dardieri*). Four microfacies–types were differentiated (4–7 in Table 1):

- Microfacies 4: Wackestone with peloids (Table 1). This is characterized by a micritic matrix with common peloids and bioclasts (mainly gastropod and bivalve fragments, Fig. 4d, and serpulids), foraminifera (*Quinqueloculina*, Fig. 5c, d, *Textularia*, Fig. 6c, *Trochammina,* Figs. 5i, 6b, *Reophax* and *Charentia*), ostracods and remains of dasyclad green algae and scarce charophyta. Lumps and intraclasts are locally common (beds − 4 and 12; Fig. 3).
- Microfacies 5: Wackestone with miliolids (Table 1, Fig. 4e). This is characterized by a micritic matrix, partially dolomitized, with benthic foraminifera (*Quinqueloculina*, Fig. 5c, d, *Trochammina*, Figs. 5i, 6b, *Vinelloidea*, *Placopsilina*, *Ophthalmidium*, Fig. 6f, *Glomospira*, *Ammobaculites*, Fig. 5g, h, *Triloculina*, *Choffatella*, Fig. 5b, *Sabaudia*, Fig. 6d, *Textularia*, Fig. 6c, and orbitolinids, Figs. 5a, 6a), and ostracods (*Paracypris*, Fig. 5m, *Platycythereis*, Fig. 5n, *Asciocythere*, Fig. 5o, and *Bythocypris*, Fig. 5l). Mollusc fragments are present in variable abundance. This microfacies is frequent in the lower part of the Bedmar-Jódar section (Fig. 3). Fenestrae are common in some beds.
- Microfacies 6: Wackestone with charophyta (Table 1, Fig. 4f). This is characterized by a micritic matrix with common burrows and fenestrae; locally these microfacies are dolomitized. Among the bioclasts, oogonia (Fig. 6) and utricules of characea and clavatoracea dominate (mainly *Atopochara*). Moreover, *Cayeuxia* (Fig. 6l) is present. This microfacies is observed in the upper part of the studied section, in one case associated with a bed whose top showed mud cracks and dense borings, and a convex top surface described as a "buildup" (bed 46; Fig. 3). Bed 46 is also affected by two paleofracture systems (N80°E and N30°E), whose surfaces contain borings.
- Microfacies 7: Wackestone with orbitolinids (Table 1). This is composed of a micritic matrix with peloids and orbitolinids and common burrows. Beds 4, 42 and 50 (Fig. 3) contain *Orbitolina* (*Mesorbitolina*) *texana*. Other bioclasts are benthic foraminifera (mainly *Quinqueloculina*, Fig. 5c, d, and secondarily *Textularia*, Fig. 6c, *Glomospira*, *Sabaudia*, Fig. 6d, and *Trochammina,* Fig. 6b), fragments of serpulids, gastropods and rudists (*Mathesia dardieri*), charophyta and dasyclad green algae (*Salpingoporella*, Fig. 5s). In addition, very fine quartz grains were observed. This microfacies is mainly present in the upper part of the studied section (Fig. 3). The top of the bed 50 (Fig. 3) is a bored surface.

## Lithofacies association 3: Limestone with packstone texture

This association is composed of three microfacies types (8–10 in Table 1):

- Microfacies 8: Packstone with orbitolinids (Table 1). This microfacies is recorded in the lower part of the section. It is a packed accumulation of planar orbitolinids, a so-

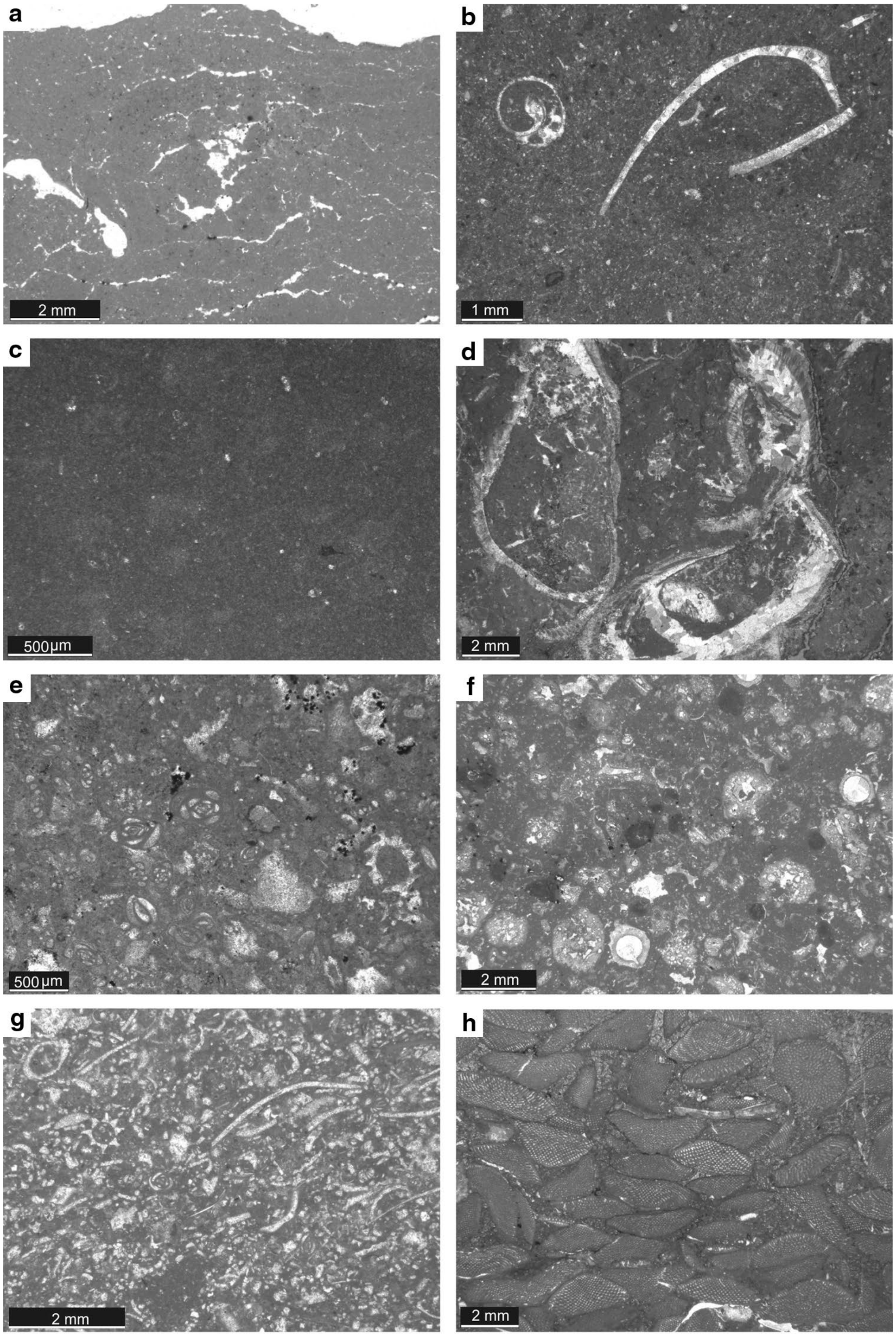

**Fig. 4** Microscopic images of the microfacies shown in Table 1. **a** Mudstone with bioclasts and mud cracks. **b** Mudstone with miliolids and mollusc fragments. **c** Mudstone. **d** Wackestone with peloids and some rudist sections. **e** Wackestone with miliolids and characeae. **f** Wackestone with charophyta and some oogonia and utricules. **g** Packstone with bioclasts, miliolids and characeae. **h** Grainstone with orbitolinids (orbitolinite)

called "orbitolina facies" sensu Vilas et al. (1995). Other fossils present are small benthic foraminifera (mainly *Quinqueloculina*, Fig. 6g, and less common *Textularia*, Fig. 6c, *Trochammina*, Fig. 6b, *Lenticulina*, *Bolivina*, Fig. 5j, *Gyroidinoides* and *Vinelloidea*), ostracods (e.g., *Platycythereis*, Fig. 5n), gastropods and fragments of rudists and other bivalves. Small gastropods can be very abundant (bed 1; Fig. 3). Bed 2 (Fig. 3), in the lower part of the section, shows a paleofracture system (N160°E) and mud cracks on the top.

- Microfacies 9: Packstone with bioclasts (Table 1, Fig. 4g). This is a bioclastic-rich microfacies with common miliolids, fragments of molluscs (bivalves and gastropods) and benthic foraminifera (mainly agglutinated forms and lagenina). Quartz grains are also present.

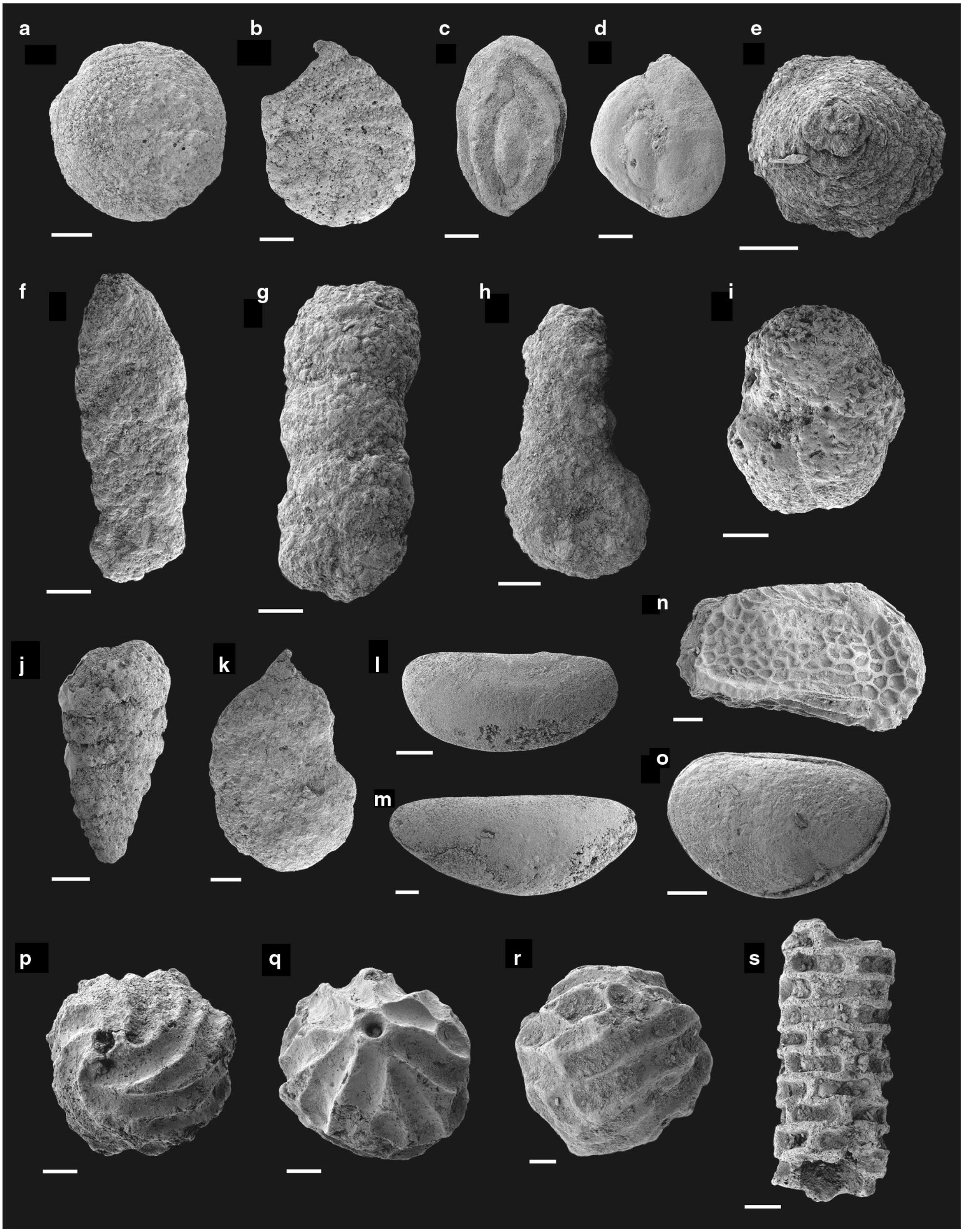

**Fig. 5** Images of foraminifera and ostracods shown from the sieve. **a** *Orbitolinid*; **b** *Choffatella* sp.; **c**, **d** *Quinqueloculina* sp.; **e** *Sabaudia minuta*; **f** *Flabellammina* sp.; **g** *Ammobaculites* sp.; **h** *Ammobaculites* sp.; **i** *Trochammina* sp.; **j** *Bolivina* sp.; **k** *Astacolus* sp.; **l** *Bythocypris* sp.; **m** *Paracypris*; **n** *Platycythereis* gr. *algarvensis*; **o** *Asciocythere cinctorensis*; P-R.-, Gyrogonites of *Atopochara* sp.; S. *Salpingoporella* sp. The *scale bar* is 100 µm. A from sample RO-C-451. **b**, **c**, **n** and **s** from sample RO-C-455. **e**, **f**, **h**, **k**, **m**, **p**, **q** from sample RO-C-468A, **r** from sample RO-C-481B, **j** from sample RO-C-N2

- Microfacies 10: Packstone with peloids (Table 1). It is a microfacies with abundant peloids, bioclasts and fenestrae. Mollusc fragments are very scarce. Among the foraminifera, orbitolinids *Orbitolina* (*Mesorbitolina*) *texana* and *Quinqueloculina* (Fig. 5c, d) are dominant. Other less common foraminifera are *Ammobaculites* (Fig. 5g, h), *Glomospira*, *Placopsilina*, *Ophthalmidium* (Fig. 6f), *Triloculina*, *Trochammina* (Fig. 6b), and *Vinelloidea*. The most conspicuous bored surface in the section is developed at the top of a bed with this type of microfacies (bed 26; Fig. 3).

### Lithofacies association 4: Limestone with grainstone texture

Two microfacies types made up this association (11–12, Table 1), recorded in the lower part of the studied section (Fig. 3).

- Microfacies 11: Grainstone with orbitolinids (Table 1, Fig. 4h). This is an orbitolinid facies with a very dense packing of shells of *Orbitolina* (*Mesorbitolina) texana*. Other foraminifera are *Quinqueloculina* (Fig. 5c, d), *Trochammina* (Fig. 5i) and *Glomospira*. Scarce fossil remains of *Salpingoporella* (Fig. 5s) are also present.
- Microfacies 12: Grainstone with peloids (Table 1). This is a dense accumulation of bioclasts (mollusc and echinoderm fragments), foraminifera (mainly *Orbitolina* (*Mesorbitolina*) *texana* and *Quinqueloculina*, Fig. 5c, d) within a microsparite-rich matrix of peloids and lumps. Contacts between orbitolinid shells are locally stylolitic surfaces. Locally this microfacies is rich in fenestrae (Fig. 3).

## Ichnology

Two major groups of trace fossils have been differentiated: burrows and borings (Fig. 7).

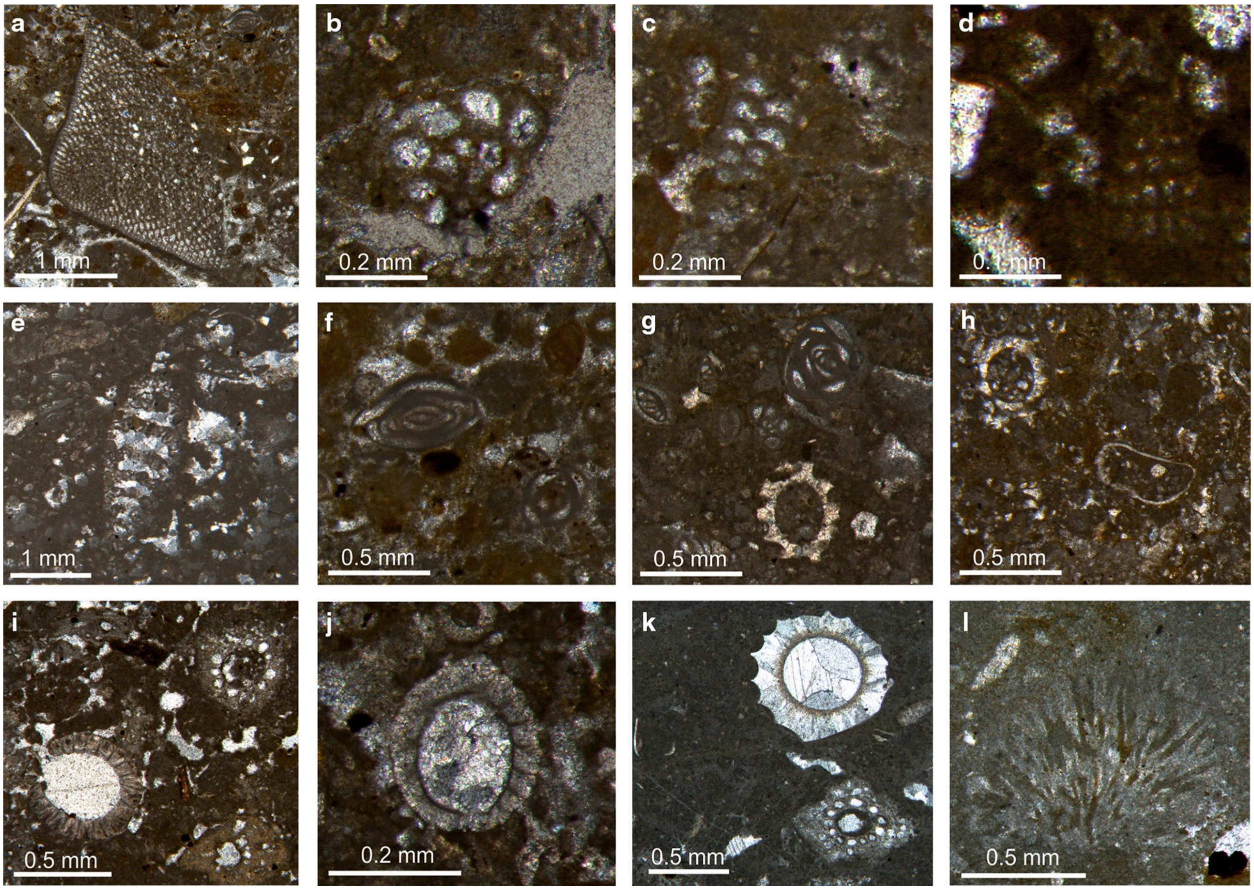

**Fig. 6** Microscopic images of some characteristic microfossils. **a** *Mesorbitolina* sp.; **b** *Trochammina* sp.; **c** *Textularia* sp.; **d** *Sabaudia* sp.; **e** Lituolid; **f** *Ophthalmidium* sp. **g** Miliolids (*Quinqueloculina* sp.) and charophyte gyrogonite; **h** Charophyte gyrogonite (left) and ostracod (right); **i** Gyrogonite of charophyte (left) and thallus (right); **j** Gyrogonite of charophyte; **k** Gyrogonite of charophyte (upper part) and thallus (lower part); **l** *Cayeuxia*

## Burrows

Among the burrows, the ichnogenera ?*Arenicolites* and *Thalassinoides* were identified (Fig. 7a), as well as paired holes corresponding to *Diplocraterion* or *Rhizocorallium*.

- ?*Arenicolites* isp. Circular structures arranged in pairs; they are very common on some of the studied surfaces. These structures are 30–50 mm apart and they are around 10 mm in diameter. In most of the cases, spreiten between pairs of holes were not observed, thus allowing

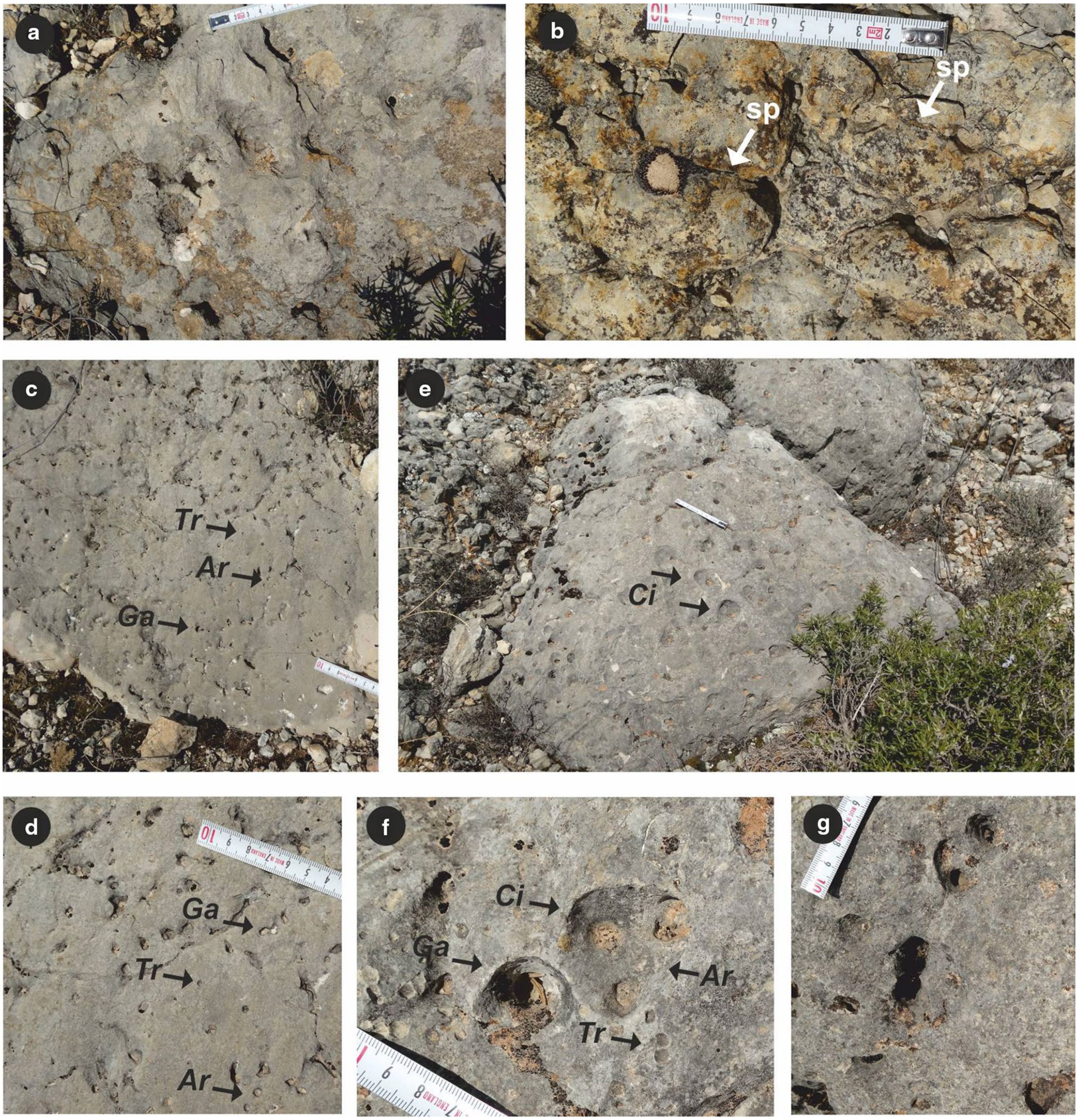

**Fig. 7** Trace fossils from the Sierra de Bedmar-Jódar section. **a** Surface of bed 26 showing irregular branched structures infilled with orange material assigned to *Thalassinoides* isp. **b** Surface of bed 31 showing paired holes with possible spreiten (sp) assigned to *Diplocraterion* isp. **c** Surface of bed 35 showing paired holes assigned to ?*Arenicolites* isp (*Ar*) as well as individual holes of *Gastrochaenolites* isp. (*Ga*) and *Trypanites* isp. (*Tr*). **d** Close-up view of surface bed 35 with paired holes assigned to ?*Arenicolites* isp. (*Ar*), and individual holes assigned to *Gastrochaenolites* isp. (*Ga*) and *Trypanites* isp. (*Tr*). **e** Surface of bed 46 with large structures, more or less hemispherical shallow depressions assigned to *Circolites* isp. (*Ci*). **f** Close-up view of *Circolites* isp. (*Ci*) cross-cutted by paired holes (?*Arenicolites*; *Ar*) and individual holes of *Gastrochaenolites* isp. (*Ga*) and *Trypanites* isp. (*Tr*). **g** Close-up view with individual holes touching one another assigned to *Gastrochaenolites* isp

assignation to ?*Arenicolites* Salter 1857, as vertical U–tubes without spreiten (after Fürsich 1974), excluding the assignation to U–shaped spreiten structures, such as the ichnogenera *Diplocraterion* Torell 1870, *Rhizocorallium* Zenker, 1836 or *Ilmenichnus* Hecker 1980. Notwithstanding, this interpretation may be not conclusive in all cases because of the possible absence of spreiten in the upper part of U–shaped spreiten structures such as *Diplocraterion* and *Rhizocorallium*. *Arenicolites* is interpreted as a burrow of annelids, particularly polychaetes (Hakes 1976; Chamberlain 1978) or crustacean-like organisms (Goldring 1962). ?*Arenicolites* is recorded in the upper part of the section, at the top of beds 29, 31, 35, 46 and 52 (Figs. 3, 7b–d).

- Locally, paired holes show a possible spreiten between them, which can be related to U–shaped spreiten burrows (Fig. 7b). The absence of complete structures impedes discrimination between *Rhizocorallium*, which is oriented obliquely to horizontally with respect to the bedding plane, and *Diplocraterion*, with predominantly a vertical orientation. Only one vertical structure, 6 cm in length, which is weakly displayed (bed 46, Fig. 3), could support the presence of *Diplocraterion*. Funnel shapes of the paired apertures were occasionally observed, but preservation may be conditioned by minor erosion of the upper part of the U–tunnels. Potential *Diplocraterion* were recorded in the upper part of the studied section (beds 31, 46 and 52; Figs. 3, 7b, e).
- *Thalassinoides* isp. Irregular, tubular burrows with branches that are Y– to T–shaped (Fig. 7a). Horizontal branching is predominant, determining a weak, polygonal network. Filling material is different from the host sediment, with a clear variation in colour, showing an orange tone with respect to the grey host sediment. These specimens can be assigned to the ichnogenus *Thalassinoides* Ehrenberg, 1944 as three-dimensional systems of cylindrical to elliptical burrows, mainly smooth-walled with variable size, having branches that are Y– to T–shaped, commonly enlarged at the bifurcation points. Irregular configuration makes it difficult to measure individual burrows, which are generally more than 1 cm wide and more than 10 cm long. Occasionally, holes 2–3 cm in diameter were observed, which could correspond to vertical shafts connected to the surface. The absence of pellets and scratch marks allows for differentiation from the similar structures of *Ophiomorpha* and *Spongeliomorpha,* respectively. *Thalassinoides* is usually interpreted as a fodinichnial structure (e.g., Ekdale 1992; Bromley 1996), but also has been interpreted as a domichnial burrow (e.g., Myrow 1995; Buatois et al. 2002), mostly attributed to crustaceans (e.g., Frey et al. 1984; Bromley 1996) or other types of arthropods (Ekdale 1992). The lower part of the section is dominated by assemblages composed almost exclusively by *Thalassinoides* (beds 2–26; Figs. 3, 7a), the most prominent beds being those related to the *Orbitolina* facies, although they are also present in micritic facies (e.g., bed 31, with microfacies–type 2; Fig. 3 and Table 1).

## Borings

Among the borings, the ichnogenera *Circolites*, *Gastrochaenolites* and *Trypanites* have been identified (Fig. 7C, D, E, F, G).

- *Circolites* isp. Large structures, sub-hemispherical shallow depressions (around 3 cm in diameter, and 0.5–2 cm in depth) were recorded in different surfaces (upper and lateral) at the "buildup" appearance beds (see below; Fig. 7d, e). This general shape allows assignation, in general terms, to the ichnogenus *Circolites* Mikuláš 1992, a fossil structure interpreted as an echinoid boring. Occasionally, inside *Circolites*, smaller holes probably belonging to *Gastrochaenolites* and *Trypanites* are observed. In places relatively deep grooves are seen associated with *Circolites*, resembling structures recently defined by Santos et al. (2015) as *Ericichnus*, groove-shaped borings related to the boring activity of regular sea urchins. *Circolites* was recorded at the top of bed 46 (Figs. 3, 7e, f).

*Circolites* is interpreted as a dwelling structure where sea-urchins are protected from predators and wave surge, and where they occasionally act as macro-suspension feeders trapping material brought into the boring by the rising tide (Asgaard and Bromley 2006; Santos et al. 2015). Hernández and Russel (2010) also attribute these pits to a more hospitable microhabitat by retaining water and moderating temperatures, and desiccation during exposure at low tide. At present, in the Mediterranean Sea, regular echinoids (*Paracentrotus lividus* Lamarck 1816) responsible for *Circolites* borings mainly inhabit extremely shallow rockgrounds between zero and − 2 m (Martinell 1981; Frantzis et al. 1992; Santos et al. 2008). The upper limit for this species is controlled by desiccation (Boudouresque and Verlaque 2001). Johnson et al. (2011) used the presence of *Circolites* at Cala Cingoya on Menorca Island (Spain) as an indicator of the highest position of the shoreline.

- *Gastrochaenolites* isp. Circular, mainly isolated holes were frequently observed on the top surfaces of continuous beds, but also in isolated blocks (e.g., bed 46, Fig. 3; see below). In most cases, individual holes, interpreted as *Gastrochaenolites*, have sharp walls. However, the local presence of a calcareous lining as well as the presence of individual holes touching one another, similar to cross sections of structures assigned to *Gastrochaenolites* (i.e., Kelly and Bromley 1984; Domènech et al. 2001), allows the assignation to this ichnogenera. *Gastrochaenolites* Leymerie 1842, refers to clavate or teardrop-like forms, commonly with a circular cross section, but also oval or dumb-bell shaped, and usually having a neck-like upper portion, although a wide range of morphologies has been related to different species (Kelly and Bromley 1984; Wilson 2007). The absence of vertical cross sections impedes recognition of longitudinal sections of the structures, impeding ichnospecies differentiation and therefore the use of the name at a generic level. Only occasionally, the shape of the aperture with the presence of individual holes in touch resembles the sections illustrated by *G. dijugus* and *G. cluniformis* illustrated in text-Fig. 3 by Kelly and Bromley (1984). *Gastrochaenolites* was recorded in the upper part of the section (beds 29, 35 and 46; Figs. 3, 7c, d, f, g).

*Gastrochaenolites* is usually referred to as borings in lithic substrates of endolithic bivalves. Other tracemakers may be involved (Savazzi 1999; Ekdale and Bromley 2001; Taylor and Wilson 2003; Benner et al. 2004; Bromley 2004; Wilson 2007), as found in a variety of hard substrates including carbonate rocky shores (e.g., de Gibert et al. 1998; Domènech et al. 2001; Johnson et al. 2011), shelly (Farinati and Zavala 2002), bone and coprolites (Tapanilla et al. 2004), metamorphic rocks (Buatois and Encinas 2011), basaltic substrates (Santos et al. 2011, 2012), and even fan-delta conglomerates (Uchman et al. 2017). Bivalve borings are domichnia-constructed for filter feeding.

- *Trypanites* isp. Simple, smaller, circular traces < 3 mm in diameter were recognized. They are commonly dispersed on the top bed surface. They are registered as sub-circular holes, with sharp burrow walls and no coherent calcareous lining. According to the size, these structures could correspond to the ichnogenus *Trypanites* Mägdefrau 1932. *Trypanites* refers to simple cylindrical, unbranched borings with a single aperture, lacking a coherent calcareous lining (Mägdefrau 1932; Kobluk and Nemcsok 1982; Kelly and Bromley 1984; Nield 1984). Bromley (1972) extended the ichnogenera to cover a wider range of single-entrance boring forms, including clavate ones. The absence of complete structures impedes a conclusive differentiation with similar forms as *Palaeosabella*; the former are cylindrical and the latter slightly expand distally, according to Bromley (2004). *Trypanites* is generally considered a worm boring, produced by sipunculan worms or polychaetes such as dominichnia for filter feeding (Rice 1969; Bromley 1972, 1978, 2004; Kobluk and Nemcsok 1982; Ekdale and Bromley 2001; Taylor and Wilson 2003; Wilson 2007). These borings were recorded in the upper part of the section, on the tops of beds 29, 35 and 46 (Figs. 3, 7c–e).

## Discussion

### Facies and sedimentary environments

The four lithofacies associations identified in the studied Bedmar-Jódar section are representative of different shallow-marine carbonate platform environments.

Lithofacies association 1, marl and marly limestone with mudstone texture and miliolids, bioclasts and peloids, was deposited in shallow, low-energy, lagoon-protected environments (e.g., Tucker and Wright 1990). The miliolids correspond mainly to *Quinqueloculina*, a genus indicative of very shallow water (Bhalla and Abba 1984; Hughes 2004). Modern *Quinqueloculina* are typical of shallow carbonate platforms (Muolfi-El-Houari et al. 1999; Halfar et al. 2000) and the intertidal zone (Horton et al. 1999; Vakicek et al. 2000), low-energy lagoons and shoals (Gischler et al. 2003). The presence of rudists, corals, algal remains (*Atopochara*, *Salpingoporella* and *Cayeuxia*; Fig. 6l) and fenestrae indicates variations in the water depth, from subtidal to intertidal conditions. *Atopochara trivolvis* tolerates a wide range of salinity from fresh to brackish water (Souliemarsche 1994; Vicente and Martín-Closas 2013), hence the presence of *A. trivolvis* indicates a margin-littoral context and the influence of fresh water, which is also consistent with the presence of quartz, both indicating a continental input. The predominance of mud-rich lithologies with an oligotrophic fauna (ostracods and miliolids) together with the low diversity of the foraminiferal assemblage would indicate restricted water circulation with low hydraulic energy. The scarce record of *Lenticulina* and *Gyroidinoides* in microfacies 2 (typical of outer shelf, e.g., Reolid et al. 2016) is probably related to transport into the lagoon. The top of some beds is characterized by dense borings (beds 29 and 35i; Figs. 3, 7c) such as *Trypanites* and *Gastrochaenolites* and by burrows (beds 31 and 52; Figs. 3 and 7b) such as *Thalassinoides* and ?*Arenicolites*. A similar trace-fossil assemblage is described in the lower Aptian of Saudi Arabia (Hughes 2003) and the Bolkar Mountains, Turkey (Tasli et al. 2006).

Lithofacies association 2, wackestone with peloids, miliolids (mainly *Quinqueloculina*), charophyta and orbitolinids (Microfacies 4–7, Table 1) was deposited in lagoonal environments with a significant influence from exposed areas, as suggested by the common presence of charophyta (mainly genus *Atopochara*; Fig. 5p–r), which live in fresh water. Other algae are *Salpingoporella* (Fig. 5s, o) and *Cayeuxia* (Fig. 6l), typical of shallow-marine waters. The ostracods *Platycythereis* (Fig. 5n), *Asciocythere* (Fig. 5o) and *Bythocypris* (Fig. 5l) indicate truly marine conditions (Schudack and Schudack 2009; Wilkinson 2011). This lagoon is interpreted as having generally subtidal conditions, but the presence of mud cracks and fenestrae in a top surface with dense borings (*Circolites*, *Trypanites* and *Gastrochaenolites;* Fig. 7e–g) indicates synsedimentary cementation typical of intertidal to supratidal conditions, pointing to relative sea-level oscillations. The presence of two systems of paleofractures (bed 46, wackestone with charophyta; Fig. 3) affecting the same bed suggests that this shallowing-upwards evolution (from subtidal to intertidal and supratidal) could be related with an extensional tectonic phase.

Lithofacies associations 3 and 4, packstone with orbitolinids, bioclasts and peloids (Microfacies 8, 9, 10, Table 1), as well as the grainstone texture with orbitolinids and peloids (Microfacies 11, 12, Table 1), are indicative of high-energy environments, especially in the case of the orbitolinid facies (worn shells of orbitolinids, dense packing of shells). These facies, mainly in the case of orbitolinid, could correspond to migrating sand bars bounding the lagoon. The presence of *Lenticulina*, *Gyroidinoides* and *Bolivina* (Figs. 5j) confirm a higher influence from offshore conditions due to the fact that these foraminifera are typical of outer-shelf settings (e.g., Gebhardt et al. 2004; Reolid et al. 2015). The scarce amount of green algae (*Salpingoporella*, Fig. 5s) and the absence of charophyta are consistent with this interpretation. These bars were locally affected by burrowers (*Thalassinoides* and ?*Arenicolites* tracemakers). This model is in agreement with that proposed by Vilas et al. (1995), who interpreted the orbitolinid facies in the Prebetic as developed during transgressive episodes, in some cases across the whole platform, from the littoral to the outer-shelf environments. In the example studied here, the orbitolinid bed was developed in the inner platform as bars separating the lagoon from the open-platform environments. Consequently, these environments were very sensitive to relative sea-level changes, which explains the observed cyclic pattern, mostly from subtidal to intertidal conditions. The presence of paleofractures at the top of some orbitolinid levels (bed 2, Fig. 3) provides evidence that extensional tectonics were the mechanism triggering the relative sea-level changes and, as a result, the local development of supratidal fenestrae and hardground surfaces.

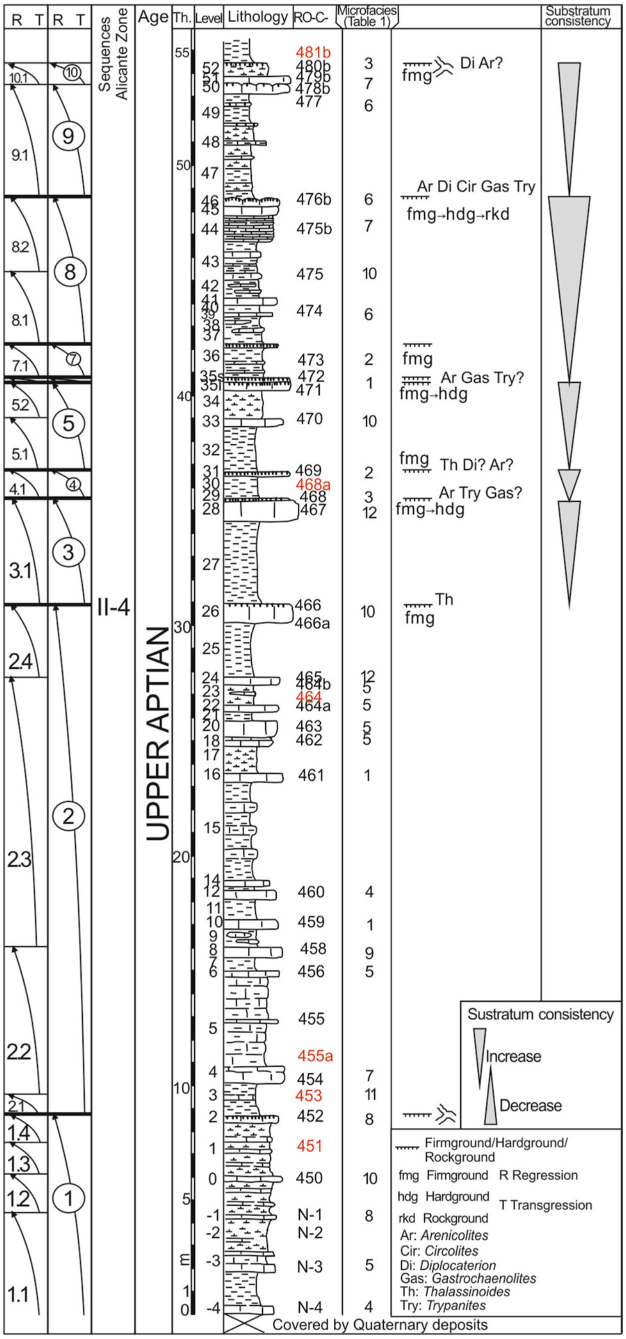

**Fig. 8** Stratigraphic section with the evolution of the substratum consistency and elementary cycles shown in the section

## Trace fossils and substrate consistency

Trace fossil assemblages show a clear stratigraphic distribution with variations in ichnological features such as abundance, composition, diversity and size. The lower part of the section is dominated by assemblages composed almost exclusively of *Thalassinoides* (beds 2–26; Figs. 3, 7 and 8). In the upper part of the section, several beds show a more diverse trace-fossil assemblage. From bottom to top these beds are 26, 29, 31, 35i, 46 and 52 (Figs. 3 and 8).

- Bed 26 (microfacies 10, packstone with peloids, Table 1) is characterized by an irregular surface with variations in colour, orange and grey, showing the presence of *Thalassinoides* (Fig. 8). No other bioturbation or boring structures were recognized. *Thalassinoides* is registered in a wide variety of substrate consistencies, from soft- to hard-grounds. However, in the case studied, the exclusiveness of *Thalassinoides* and the absence of borings could be related to stable, fine-grained substrates, in consolidated firmground conditions, but not hardgrounds. *Thalassinoides* is one of the most common ichnofossils of the *Glossifungites* ichnofacies, which developed in stable, cohesive substrates (firmgrounds), unlithified, especially semi-consolidated carbonate firmgrounds, or stable, cohesive, partially dewatered muddy substrates (Pemberton and Frey 1985; Lewis and Ekdale 1992; MacEachern et al. 1992, 2007; Pemberton et al. 1992, 2001, 2004; Pemberton and MacEachern 2005; Rodríguez-Tovar et al. 2007). Colonization by the *Thalassinoides* tracemaker could be related with a decrease in the rate of sedimentation, allowing the development of initial phases of firmgrounds (Fig. 8); nevertheless, continuous sedimentation prevented development of later phases of firmground colonization or even development of a hardground. Elsewhere, minor erosion causing exhumation of buried firmgrounds could be possible. Continuity in sedimentation after colonization by the *Thalassinoides* tracemaker is also supported by the presence of the final apertures of the shaft as revealed by the holes associated with the horizontal traces.

- Bed 29 (microfacies 3, mudstone with peloids; Fig. 3, Table 1) shows a more or less planar surface with frequent bioturbation structures as paired and isolated holes, characterized by a small diameter (mode of 4 mm). Paired holes are the dominant traces, probably corresponding to small ?*Arenicolites*, whereas smaller ones could correspond to *Trypanites* borings. Rare small *Gastrochaenolites* borings are also present. Dominance of ?*Arenicolites* could be interpreted as the result of colonization in generalized firmground conditions. *Arenicolites* was recorded from softgrounds to firmgrounds, but not in hardgrounds (Reolid et al. 2010), being a common trace of the *Glossifungites* ichnofacies (Pemberton et al. 2001; MacEachern et al. 2007, 2012; Buatois and Mángano 2011). The possible presence of *Gastrochaenolites* and *Trypanites* could reflect a progressive increase in substrate firmness. *Gastrochaenolites* has usually been interpreted as a boring in lithic substrates (Kelly and Bromley 1984), and is therefore related to rockgrounds and hardgrounds. However, this ichnogenus has also been recognized in firm substrates, in some cases together with traces typical of firmgrounds, such as *Thalassinoides* (Carmona et al. 2006, 2007). Moreover, firmground *Gastrochaenolites* is considered to be a common structure in the *Glossifungites* ichnofacies (e.g., Pemberton et al. 2001). *Trypanites* is an ichnotaxon exclusive to lithified substrates such as hardgrounds and rockgrounds, it being the eponym trace fossil of the *Trypanites* ichnofacies (Seilacher 1967) and of the *Entobia* ichnofacies (according to Bromley and Asgaard 1993). *Gastrochaenolites* can be registered together with *Arenicolites* in the firmground *Glossifungites* ichnofacies, but also together with *Trypanites* in hardgrounds (Fig. 8).
- Bed 31 (microfacies 2, mudstone with miliolids, Table 1) has a slightly irregular surface, yellow in colour, which can be related to the presence of the *Thalassinoides* ichnofabrics. Paired holes, in some cases with weakly defined spreiten between holes, support the presence of *Diplocraterion* and, maybe, ?*Arenicolites* (Fig. 3, Fig. 7b). The record of *Thalassinoides* and the absence of boring structures, could be related to stable, fine-grained substrates, in consolidated firmground conditions, but not hardgrounds.
- Bed 35i (microfacies 3, mudstone with bioclasts, Table 1) shows a relatively planar surface, characterized by a moderately abundant trace-fossil assemblage, with dominance of medium-size ?*Arenicolites* and *Gastrochaenolites*. Some smaller holes can be attributed to *Trypanites*. This bed 35i (Fig. 3) is capped by bed 35 s, characterized by a very flat surface, similar to that of bed 29, showing a trace fossil assemblage dominated by small structures, mainly *Gastrochaenolites* and ?*Arenicolites* (Fig. 7c, d). Moreover, smaller isolated traces, probably *Trypanites*, are abundant. On this surface, also irregular, slightly sinuous horizontal traces (?*Meandropolipora*) were observed, but any conclusive assignation is difficult. The record of ?*Arenicolites* together with *Gastrochaenolites* and *Trypanites* could reflect a progressive increase in substrate firmness from firm- to hard-ground (Fig. 8).
- Bed 46 (wackestone with charophyta, microfacies 6, Table 1) reveals particular lithological and ichnological features, showing significant changes with respect to previous beds. In the former, this bed does not show a continuous record but a particular "boulder" or buildup appearance (Fig. 3). Regarding the ichnological features, a higher abundance, diversity and size of trace fossils is observed in bed 46. Traces are located not only in the upper surface, but also in variable positions of the buildup. Indeed, this trace fossil assemblage shows the highest diversity among the studied sections, as well as the largest structures, with burrows ?*Arenicolites* and *Diplocraterion*, and borings *Circolites*, *Gastrochaenolites* and *Trypanites*. This assemblage reveals a progressive increase in consistency from firmground mainly associated with the burrows to well-developed hardgrounds/rockgrounds as interpreted by the diverse boring suite (Fig. 8). Locally, *Gastrochaenolites* and *Trypanites* occur inside the cavity of *Circolites* (Fig. 7f), which is in agreement with previous interpretations on *Circolites* producers, as pioneer echinoids (Johnson et al. 2011; Santos et al. 2008, 2011), followed by lithophagid

bivalves and worm-like animals respectively producing *Gastrochaenolites* and *Trypanites*,

- Bed 52 (mudstone with peloids, microfacies 3, Table 1) shows a slightly irregular surface (Fig. 3), locally yellow in colour, similar to bed 31. As in bed 31, paired holes, in some examples with a weakly defined spreite between holes, support the presence of *Diplocraterion*, for those structures with spreite, and possibly ?*Arenicolites* for those without spreite. The absence of boring structures could be related to the cohesive substrate of firmgrounds (Fig. 8).

## Stratigraphic evolution of trace fossil assemblages

According to the distribution of the ichnological features, i.e. trace-fossil assemblages, abundance and size, a general pattern can be established, showing a more or less clear repetition throughout the studied section. This pattern and the subsequent repetitions may reflect variations in substrate consistency, showing a progressive increase in firmness, probably associated with variations in the sedimentation rate induced by changes in relative sea level.

Thus, from bed 26 to bed 29 (Fig. 8) an increase in substrate consistency is revealed by the replacement of a firmground suite exclusively with *Thalassinoides* to a more diverse firmground-hardground assemblage with ?*Arenicolites*-*Gastrochaenolites*-*Trypanites*.

From bed 29 to 31 a return to initial conditions can be interpreted by the presence of *Thalassinoides*. From bed 31 to beds 35i and 35s, a new increase in substrate consistency can be interpreted, ending with features similar to those of bed 29 (Fig. 8). This new phase could end in bed 35s or could continue to finish in bed 46.

The consistency is highest in bed 46 (Fig. 8), with a buildup appearance and the best preserved firmground to hardground/rockground trace fossils.

The last phase in the changing consistency of marine substrate ends in bed 52 (Fig. 8), with a firmground similar to that of bed 31, with similar trace fossils *Diplocraterion* /?*Arenicolites* and the absence of *Gastrochaenolites* and *Trypanites*.

Thus, stratigraphic changes in trace fossils, their abundance, composition and diversity are related to variations in firmness mainly associated with changes in the sedimentation rate. In the initial phases, when the rate of sedimentation is higher, stable, semi-consolidated substrates develop, allowing bioturbation exclusively by the *Thalassinoides* tracemaker. Then, in more prolonged phases when sedimentation rate decreases, firmgrounds are better developed, allowing bioturbation by the *Diplocraterion*/?*Arenicolites* tracemakers. Later phases with even lower sedimentation rates allow for the development of firmground–hardground conditions during longer times, facilitating development of a more abundant and diverse trace-fossil assemblage characterized by the presence of firmground ?*Arenicolites*, firmground-hardground *Gastrochaenolites*, and the hardground *Trypanites*. During the most prolonged phases of low sedimentation rates, even rockground borings as those of *Circolites* in bed 46 (Fig. 8) can be produced.

## Sedimentary sequences

From the stratigraphic distribution of microfacies and trace fossils throughout the section, 18 shallowing-upward, high-frequency elementary intervals, of metric scale, were differentiated (Fig. 8), included in 10 sedimentary sequences with a thickness ranging from 1 to 20 m (Fig. 8). The sequences that show a facies evolution corresponding to the shortest recognizable cycle of environmental change are called elementary sequences after the proposal of Strasser et al. (1999). These sequences are stacked into sequences of larger scale (1–20 m) that can be referred to as medium-scale sequences (op. cit.). This nomenclature is purely descriptive and does not imply any time range, as the time framework is not well known for each sequence.

Four types of high-frequency elementary sequences are distinguished on the basis of trace fossils, the consistency of the substrate interpreted from the ichnofossil assemblage, and the facies:

- Elementary sequence type 1 (Fig. 9): It begins with a marl/marly limestone layer with mudstone to wackestone texture (Lithofacies 1 and 2, Table 1) followed by a limestone bed with packstone to grainstone texture (Lithofacies 3 and 4, Table 1). The top of the elementary sequence is characterized by the absence of bioturbation structures. In this sequence the marl/marly limestone member was developed in a subtidal low-energy lagoon, whereas the limestone bed represents a high-energy intertidal bar. A shallowing-up trend is developed as a consequence of high carbonate production that outpaces the relative sea-level rise (Strasser et al. 1999; Strasser and Samankassou 2003).
- Elementary sequence type 2 (Fig. 9): These are sequences beginning with marl and marly limestone (mudstone to wackestone, Lithofacies 1 and 2, Table 1) followed by limestone (packstone to grainstone texture, Lithofacies 3 and 4, Table 1) with abundant *Thalassinoides* at the top (e.g., bed 2). This sequence evidences a transition from the lagoon to pack/grain-stone bars (locally orbitolinid bars), where a decrease in the sedimentation rate, probably related to a stabilization of the bars, favored the development of a firmground and then colonization by crustaceans (probable tracemakers of *Thalassinoides*). The presence of paleofractures shows the importance of

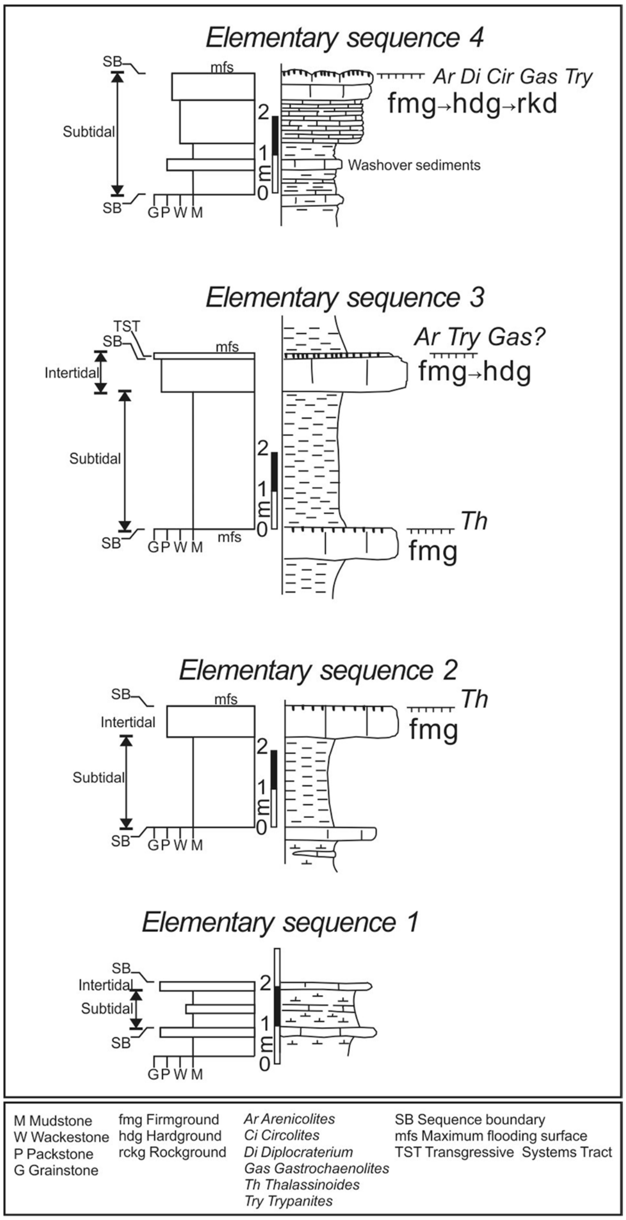

**Fig. 9** The four kinds of elementary sequences worked out from the facies, microfacies and ichnofacies analysis recognized in the studied section. For explanation see text

the extensional tectonics. This could produce an increase in the accommodation space and, possibly during a transgression, a reduction in the sedimentation rate (Hillgärtner 1998; Taylor and Wilson 2003). The carbonate factory could have shut down. As a consequence, the top of pack/grain-stone bars was colonized by the tracemakers of *Thalassinoides* and the surface developed as a firmground that could be interpreted as a maximum flooding surface.

- Elementary sequence type 3 (Fig. 9): These are represented by marl (mudstone and wackestone, Lithofacies 1 and 2, Table 1) at the base and limestone (packstone and grainstone, Lithofacies 3 and 4, Table 1) with ?*Arenicolites*, *Trypanites* and *Gastrochaenolites* in the upper part. The ichnofossil assemblage evidences a progressive increase in the substrate consistency from firmground with ?*Arenicolites* (Pemberton et al. 2001) to hardground with *Gastrochaenolites* (Domènech et al. 2001; Johnson et al. 2011), and *Trypanites* (Seilacher 1967; Bromley and Asgaard 1993). Sedimentation stopped at the top of this type of elementary sequence, favoring the development of hardground and a stratigraphic unconformity.

As in the previous elementary sequences, the development of this type is related to the carbonate production in a shallow lagoon bordered by pack/grain-stone bars. In a transgressive context (TST, Fig. 9), with high energy, the pack/grain-stone bars migrated over the lagoon sediments. Then, the water depth increased in most areas of the platform. This stopped the carbonate factory. According to Catuneanu (2006), in a slow transgression, an excess of accommodation space is created across the carbonate platform. While the platform is flooded, it favors colonization by organisms producing trace fossils and the beginning of cementation with the development of a firmground firstly, and a hardground later. In general, this evolution could be controlled by regional tectonics, because these environments belong to a fault-block carbonate platform affected by the seafloor spreading of the North Atlantic.

- Elementary sequence type 4 (Fig. 9) begins with marl and marly limestone (mudstone to packstone, Lithofacies 1–3, Table 1) at the base and limestone (wackestone of charophyta –microfacies 6-, and wackestone with orbitolinids –microfacies 7-) in the upper part. It is characterized by the presence of ?*Arenicolites*, *Diplocraterion*, *Circolites*, *Gastrochaenolites* and *Trypanites*, evidencing the transition from a firmground (record of ?*Arenicolites* and *Diplocraterion*; e.g., Pemberton et al. 2001) to a hardground/rockground (record of *Circolites*, *Gastrochaenolites* and *Trypanites*; Kelly and Bromley 1984; Bromley and Asgaard 1993; Santos et al. 2008; Johnson et al. 2011). This elemental sequence is only observed in the uppermost part of the studied stratigraphic section (bed 46). As occurred in the preceding elemental sequence, this evolution also shows a reduced sedimentation rate and the development of an unconformity. Temporal emergence of the seafloor is evidenced by the presence of mudcracks and fenestrae in the orbitolinid wackestone. The presence of the two paleofracture systems in bed 46 could reflect an important tectonic control in the development of this sequence and in the final evolution of the platform.

The distinctive feature of this latest elementary sequence is the complex evolution of its top, meaning the final stage of a lagoonal subtidal environment. In the lagoon, some bioclastic sand beds developed, interpreted as washover sediments, whose source would be the intertidal pack/grainstone bars bounding the lagoon.

As has been shown previously, the lagoon was developed in a context of high carbonate production. Hence, the presence of paleofractures could explain an increase in the accommodation space and, for elementary sequence 2, the development of a transgressive condition. Besides, the transition from firmground to hardground and rockground implied an important change in the faunas and the living conditions—nearly subaerial environments, but close to the sea-level surface.

The presence of synsedimentary paleofractures highlights the importance of extensional tectonics as a factor controlling the evolution of these sequences and, in general, in the development of the carbonate platform. This would be consistent with the fault-block carbonate platform model proposed by Ruiz-Ortiz et al. (2014) for the Prebetic of Jaén, and with the seafloor spreading of the Atlantic and the rifting affecting the Southern Iberian Palaeomargin during the Aptian (Vilas et al. 2004).

## Conclusions

Four lithofacies associations and twelve microfacies types were recognized in the studied upper Aptian section of the Sierra de Bedmar-Jódar (Prebetic of Jaén). The lithofacies associations 1 (three kinds of mudstone microfacies) and 2 (four kinds of wackestone microfacies) were developed in a shallow lagoon environment, bordered by pack/grain-stone bars, represented by lithofacies associations 3 (three kinds of packstone microfacies) and 4 (two kinds of grainstone microfacies).

In the lagoon facies, the predominance of mud-rich lithologies with an oligotrophic fauna along with the low diversity of the foraminiferal assemblage indicate restricted water circulation with low energy and the significant influence of emergent areas. These facies were developed in subtidal conditions but the presence of mud cracks, fenestrae and surfaces with dense bioturbation structures indicating episodes with synsedimentary cementation typical of the shallowest environments, as intertidal or supratidal. These features are consistent with a relative sea-level drop or local emergence that could be controlled by tectonics, as deduced by the presence of synsedimentary paleofractures in the section.

The pack/grain-stone bars bounded and separated the lagoon from the open platform. The pack/grain-stone bars were moreover very sensitive to relative sea-level changes, because firmground, hardground or rockground developed at the top of some of them.

The lower part of the section is dominated by an ichnofossil assemblage composed almost exclusively by *Thalassinoides*, whereas in the upper part a more diverse trace-fossil assemblage includes: *Thalassinoides*, ?*Arenicolites*, *Diplocraterion*, *Trypanites*, *Gastrochaenolites* and *Circolites*. The nearly exclusive presence of *Thalassinoides* is indicative of cohesive substrates, probably firmground development, whereas the evolution from firmground (*Thalassinoides* or *Thalassinoides* + ?*Arenicolites*) to hardground (*Gastrochaenolites* + *Trypanites* or ?*Arenicolites* + *Diplocraterion*), and then rockground (*Circolites* + *Gastrochaenolites* + *Trypanites*) can be interpreted on the basis of the trace-fossil assemblage.

Four types of shallowing-up elementary sequence were differentiated according to the types of lithofacies and microfacies, the trace fossils, and the evolution of substrate consistency. All the sequences show at their base a first bed representing a lagoonal environment and above it an interval with pack/grain-stone bar facies. Two important factors that conditioned the evolution of these sequences were carbonate production, and in turn the carbonate sedimentation rate, and tectonics. The shallowing-upwards elementary sequences in this part of the platform resulted from a transgressive context. The subtidal lagoonal environment stratigraphically changed to more distal facies, represented by pack/grainstone bars developed in intertidal to supratidal (firmground, hardground or rockground) environments.

**Acknowledgements** The research by Rodríguez-Tovar was funded by Project CGL2015-66835-P (Secretaría de Estado de I+D+I, Spain), the Research Group RNM-178 (Junta de Andalucía), and the Unidad Científica de Excelencia (UCE-2016-05, Univ. Granada). For the rest of the authors, funding came from Project CGL2014-55274-P (Secretaría de Estado de I+D+I, Spain) and Research Group RNM-200 (Junta de Andalucía). P.W. Skelton and J.P. Masse are thanked for their help in the determination of rudists and orbitolinids, respectively. We acknowledge Mr Antonio Piedra-Martínez, Technician of the Laboratory of Geology (University of Jaén). The comments of the Editor, Dr. Tucker, and both reviewers, Dr. Uchman and Dr. Corbí, have improved the manuscript.

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