Facies (2008) 54:61–87
DOI 10.1007/s10347-007-0125-1

ORIGINAL ARTICLE

Stratigraphy and sedimentology of Muschelkalk carbonates of the Southern Iberian Continental Palaeomargin (Siles and Cehegín Formations, Southern Spain)

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Received: 6 June 2007 / Accepted: 10 September 2007 / Published online: 2 October 2007

Abstract The Triassic sediments of the External Zones of the Betic Cordillera were deposited on the Southern Iberian Continental Palaeomargin. Two coeval Ladinian formations, namely the Siles Formation and the Cehegín Formation, are described to illustrate the facies and lithostratigraphic variability in the Muschelkalk carbonates. There has been some dispute over the number of carbonate units present in the Siles Formation. Our studies assign a tectonic origin to these recurrent carbonate units. Both formations comprise only one carbonate unit, which is correlated to the Upper Muschelkalk of the Catalan and Germanic basins and some Iberian Range sections. To characterize the sedimentological features of these formations, 14 facies were defined. The most widespread sediment was originally lime mud, although bioclastic deposits are also common. In the facies succession, a main transgressive-regressive sequence could be identified. According to the facies model proposed here, a muddy coastal and shallow-water platform prograded over mid ramp deposits. There is no evidence for a seawards reefal or oolitic-bioclastic sandy barrier. The most significant feature of this sedimentary interpretation is that these carbonate facies show clear characteristics of an epicontinental platform.

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Keywords Muschelkalk · Ladinian · Epicontinental platform · Triassic · Prebetic · Subbetic · Betic Cordillera

Introduction

The Betic Cordillera is comprised of three main groups of geological units (Fig. 1): the External Zones, the Internal Zones, and the Flysch Units of the Campo de Gibraltar Complex. The External Zones crop out extensively to the S and SE of the Iberian Massif and Guadalquivir valley and have been subdivided into two large tectonostratigraphic domains: the Prebetic and Subbetic (Fig. 1). Both domains are comprised of successions of sedimentary rocks of Triassic to Miocene age, intensely deformed but only discretely affected or unaffected by Alpine metamorphism (Martín-Algarra and Vera 2004).

In the Betic Cordillera, the carbonates of the Muschelkalk facies have long been recognized in Triassic outcrops, although tectonic deformation has hampered their in-depth study. Thus, it has been difficult to establish correlations between the stratigraphic successions described in different domains. Effectively, on several occasions, the stratigraphy of these carbonates has proven to be markedly different, depending on the area examined. Indeed, not only have stratigraphic differences been observed among Ladinian Muschelkalk outcrops, they have even been mistaken for Norian carbonates, since both involve similarly shallow-marine facies.

In a recent study of the eastern sector of the Cordillera, Pérez-Valera (2005) distinguished two formations to characterize the different types of Muschelkalk carbonate. This first study provides an interesting framework for all the outcrops of the Betic Cordillera.

In the present paper, we analyzed the outcrops of the Muschelkalk facies carbonates in the External Zones of the

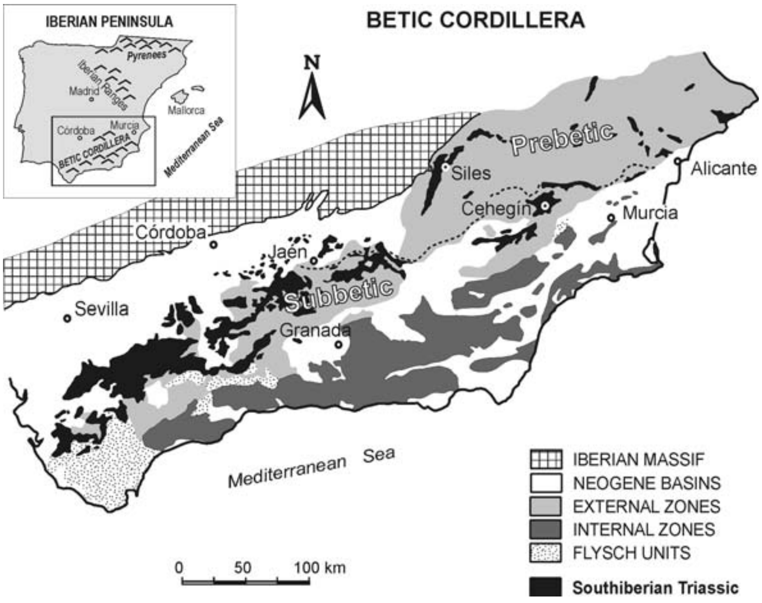


Fig. 1 Location and geological setting of the Triassic outcrops within the tectonic context of the Betic Cordillera (southern Spain). The Southiberian Triassic outcrops correspond to sediments deposited on the Southern Iberian Palaeomargin (Fig. 4) and are composed of disrupted sections of Buntsandstein, Keuper and Muschelkalk facies. The boundary between the Prebetic and Subbetic domains is indicated by a *dotted line*

Betic Cordillera to establish a reference stratigraphy and facies model. These carbonates form part of the epicontinental Triassic facies (Pérez-López 1998) deposited on the Southern Iberian Palaeomargin, and have been accordingly referred to as the Southiberian Triassic (Pérez-López 1991, 1998). At present, these carbonates of the Southern Iberian Triassic crop out throughout the Subbetic and Prebetic domains of the External Zones of the Cordillera. Their sedimentological interpretation emphasizes the complex environment of Muschelkalk facies, which cannot be related to a standard ramp or a rimmed shelf because of their significant epicontinental platform features. The last section of this paper, presents a sequence stratigraphy and correlation with other Triassic basins.

Background

Many authors began to study the Triassic outcrops of the Betic Cordillera at the beginning of the 20th century (e.g., Blumenthal 1927; Schmidt 1929; Alastrue 1943; Fallot 1945; Felgueroso and Coma 1964). The first to analyse the Muschelkalk facies in the Betic Cordillera from a perspective of stratigraphy was López-Garrido (1971), who examined the Triassic outcrops of the region of Hornos-Siles in a regional study of the Prebetic domain. This author defined the Hornos-Siles Formation to characterize all the Triassic rocks that crop out in the Prebetic domain, including the fossiliferous limestones of the Muschelkalk (Fig. 2). It was assumed that the Muschelkalk facies was comprised of three carbonate intervals, separated by detrital deposits, which would disappear towards the Iberian Massif. This stratigraphy was discussed by later authors, and based on different evidence, some claimed the existence of these three carbonate units (Máquez-Aliaga et al. 1986; Gil et al. 1987; Fernández et al. 1994) while others argued there was a single level of carbonates (Besems 1981, 1983).

Busnardo (1975) undertook the first stratigraphic study of the carbonates of the Muschelkalk facies in the central sector of the Betic Cordillera (provinces of Jaén, Granada and Córdoba). This study recognized two types of Muschelkalk facies carbonate units, which exhibited quite different stratigraphic characteristics, although no formation was formally defined by this author. According to Busnardo's interpretations, the two types of carbonate differing in terms of their stratigraphy are: the "Subbetic Muschelkalk" and the "Prebetic Muschelkalk", which belong to the Prebetic and Subbetic domains, respectively (Fig. 3).

The ideas of Busnardo (1975) were later reviewed by López-Chicano and Fernandez (1988), who considered the terms Prebetic and Subbetic inappropriate and respectively designated them "Type I" (or "Trias of Barrancos-Las Casillas") and "Type II" (or "Trias of Majanillos") (Fig. 3).

Despite the fact that all these units contain similar facies to the Muschelkalk, none of these works provided precise datings to demonstrate possible chronostratigraphic correlations or clarified the relationships of these units in the different palaeogeographic realms.

In a report by Pérez-López (1991) on the Triassic of the central sector of the Subbetic domain, although supported by previous studies, age data were provided to demonstrate that the Muschelkalk of the "Prebetic type" of Busnardo, or the "Type I" of López Chicano and Fernández, constituted a carbonate unit of Norian age, and was thereafter defined as the Zamoranos Formation (Pérez-López et al. 1992). This author dated the sediments of the Muschelkalk facies

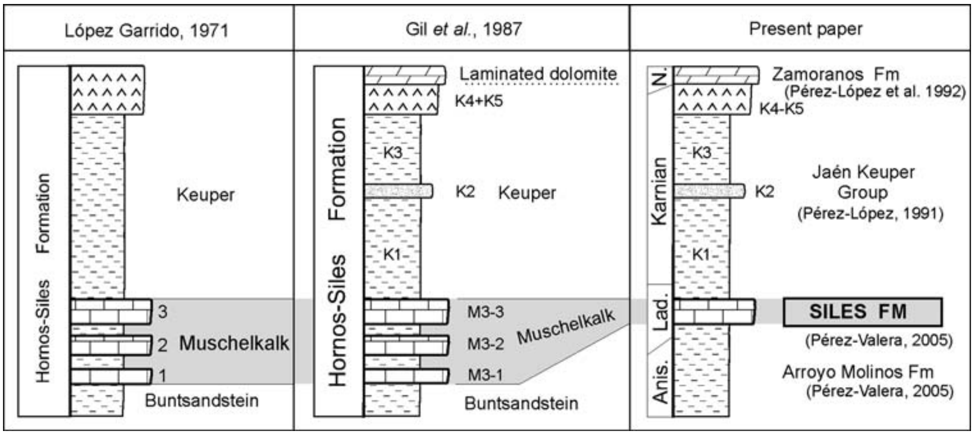


Fig. 2 Stratigraphy and designations used by different authors for the Triassic rocks of the Prebetic domain. The Siles Formation is one of the Muschelkalk formations examined in this paper that crops out near the Iberian Massif. The names of the formations used here are indicated

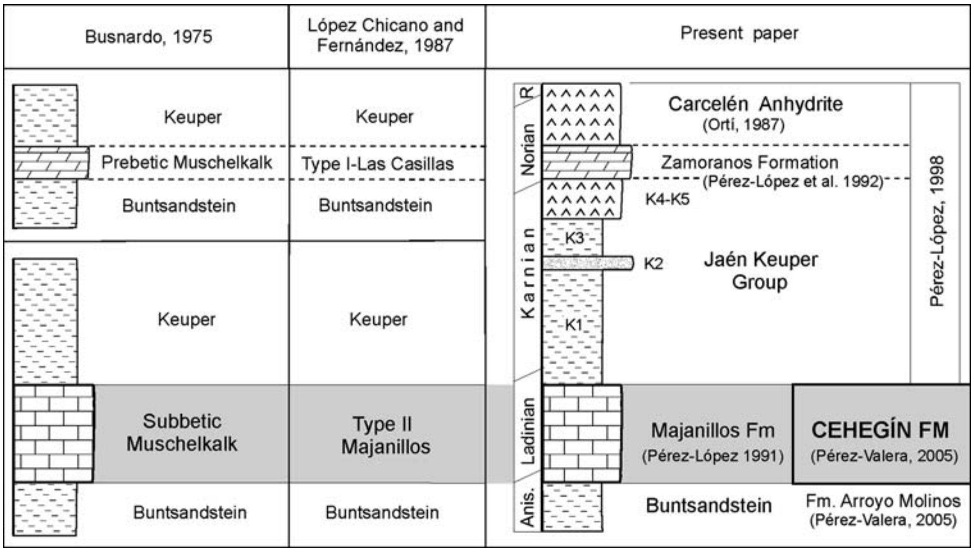


Fig. 3 Stratigraphy and denominations of the Triassic rocks in the Subbetic domain. The Cehegín Fm is one of the Muschelkalk formations that are studied in this paper. In this case outcropping far from the Iberian Massif. The names of formations used herein are included

of the Subbetic type, or "Type II", as middle-upper Ladinian, and the Majanillos Formation was informally defined to characterize the carbonates of Ladinian age included in the Muschelkalk facies of the central sector of the Subbetic domain, maintaining the denomination of the type area defined by López-Chicano and Fernández (1988).

In the present paper, we review the outcrops of the central sector of the Cordillera within the stratigraphic framework initially proposed by Perez-López (1991, 1998) and examine new outcrops of the eastern sector (Pérez-Valera 2005). Based on our findings, a stratigraphy and facies model are proposed for the Triassic carbonates that could serve as a reference for all the External Zones of the Betic Cordillera (Fig. 3).

Two formations to characterize the Muschelkalk facies

The carbonates of the Muschelkalk facies have been given different names by different authors but in most cases these are very local lithological units. In the present study of Muschelkalk facies rocks, a stratigraphy is proposed for these carbonates that is valid throughout the External Zones. The different lithological features and thicknesses of the Muschelkalk carbonates in the Prebetic and Subbetic domains justify the definition of two lithostratigraphic units to refer to the Muschelkalk, with each of these two lithostratigraphical units representing a different palaeogeographical domain.

The Siles Formation is defined to include the Muschelkalk facies carbonates cropping out mainly in the Prebetic Domain. The Siles Fm sediments were deposited in an area proximal of the Southern Iberian Palaeomargin (Fig. 4). The Cehegín Formation is defined as a formation that replaces the Majanillos Formation (Fig. 3), which corresponds to sediments deposited in more distal areas of the Southern Iberian Palaeomargin (Fig. 4). The definition of the Majanillos Fm was based on the detailed stratigraphy obtained for the carbonates of the Muschelkalk facies in the central sector of the Betic Cordillera (Pérez-López 1991, 1998). By analysing new outcrops in the eastern sector of the Betic Cordillera, the definition of the

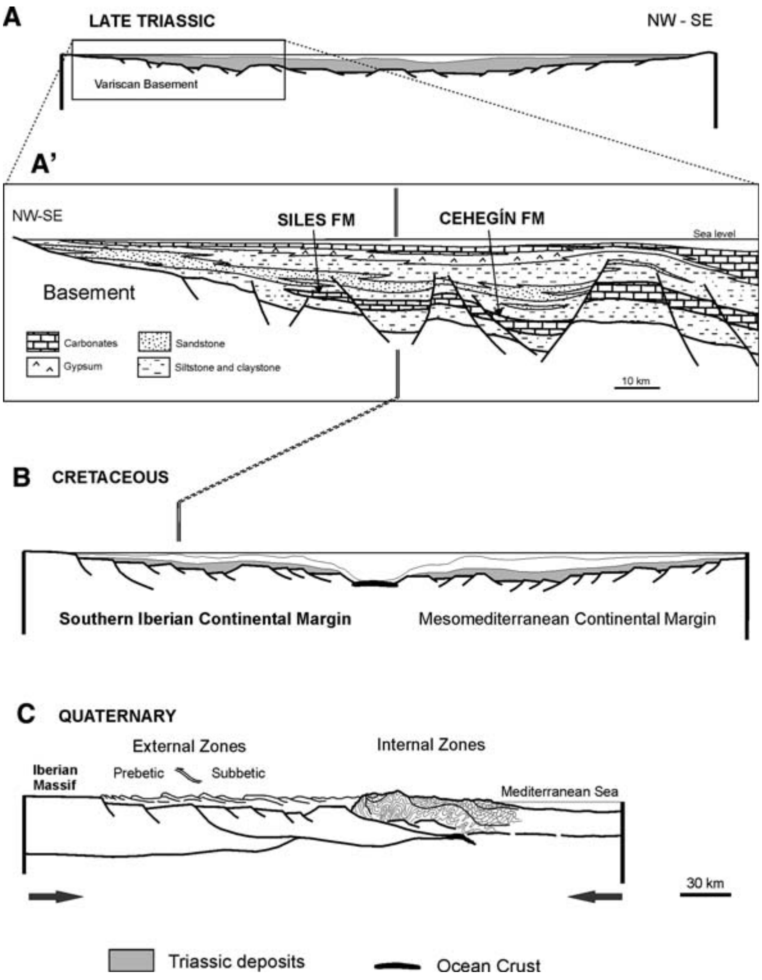


Fig. 4 Context of the formations examined: **a** Sketch of the rifting system south of Iberian Massif during the Late Triassic; **a′** Hypothetical stratigraphic framework of the Late Triassic basin indicating the positions of the Siles Fm and Cehegín Fm carbonates; **b** Development of the Southern Iberian continental palaeomargin during the Cretaceous; **c** Tectonic units of the Betic Cordillera after the Alpine orogeny where the Triassic rocks outcrop in relation to different tectonic domains. Some of the data for this figure were obtained from Pérez-López (1998) and Vera (2001)

Majanillos Fm was reviewed for the Muschelkalk facies carbonates of the External Zones in a more appropriate type area. The new formation proposed here is justified by the need to locate the type area in the eastern sector of the Betic Cordillera (north-east of the province of Murcia), where Muschelkalk carbonates crop out extensively and where there are diverse stratigraphic sections to provide a better definition of these carbonates, many of which can be correlated lithologically with the sections of the central sector of the Cordillera.

Siles Formation

The Siles Formation extends mainly along the entire portion of the Cazorla arc, from its north-eastern end (Bogarra sector) to its southernmost end (Huesa sector).

The Siles Fm takes its name from the village of Siles (Jaén province; Fig. 5). In the holostratotype (SIL-1 section), it is possible to see the Muschelkalk carbonates overlying the Buntsandstein red lutites and sandstones defined as the Arroyo Molinos Fm (Figs. 2, 6). According to its lithostratigraphy, the Siles Fm, 15–70 m thick, can be divided into two members (Fig. 6). The lower member consists of dolomites, marls, and thinly laminated marly limestones. The marly limestones are split into laminae less than 5 mm thick, and are thus characterized by paper-thin bedding. Bioclastic limestone intercalations are interpreted as storm deposits (tempestites with pot and gutter casts). The upper member consists of thin-bedded limestones with nodular structures, and marls with common bioclastic intercalations. In these carbonate beds, burrows also occur. The two members are separated by a discontinuity, which is present in all the stratigraphic sections studied (Fig. 7).

Age of the Siles Formation

The most notable fossil record in the Siles Fm is that of bivalves. Numerous species typical of the Sephardic bioprovince can be recognized: *Enantiostreon flabellum* (Schmidt), *Gervillia joleaudi* (Schmidt), *Placunopsis teruelensis* Wurm, and all are characteristic of the Ladinian (Márquez-Aliaga et al. 1986). In the present study, fossils

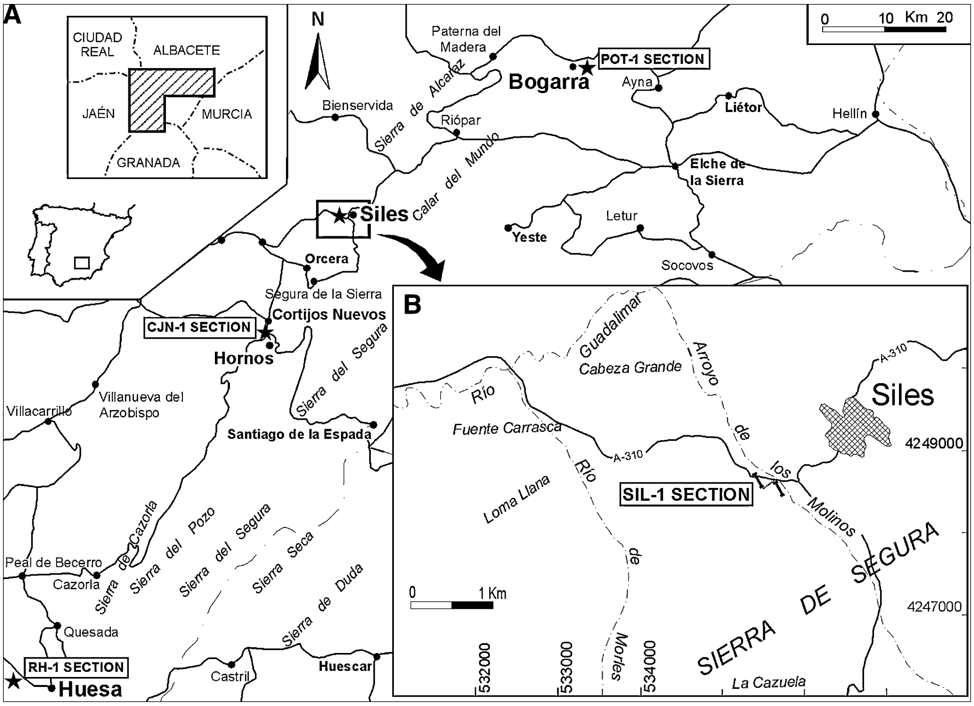


Fig. 5 **a** Geographical location of the main stratigraphic sections of the Siles Formation (RH-1, Huesa; CJN-1, Cortijos Nuevos; SIL-1, Siles and POT-1, Bogarra). **b** Holostratotype setting of the Siles Formation (SIL-1)

of these species were collected from all the sections analyzed, but no different fossil associations were found in each main section as previously reported (Márquez-Aliaga et al. 1986). Further, in a micropalaeontological study, conodontal elements were found, also typical of the Ladinian, such as *Pseudofurnishius murcianus* van der Boorgaard (Pérez-Valera 2005). Also of great value was the finding of new specimens of ammonoids of different species of *Gevanites* and *Israelites*, which along with the previously reported specimens, corroborate the Ladinian age of the carbonates of the Siles Fm and allow for improved correlation between the different stratigraphic sections.

The controversy over the carbonate units of the Siles Formation

Previous works on the Triassic of the Hornos Siles sector have proposed that the Muschelkalk succession in this sector consisted of three carbonate units separated by red siliciclastic intercalations (López-Garrido 1971; Márquez-Aliaga et al. 1986; Gil et al. 1987; Fernández et al. 1994). Besems (1981, 1983) was the first to reinterpret the stratigraphy of the Muschelkalk in this zone, concluding that there was only one carbonate unit according to palynological evidence and proposing that tectonics had caused the multiplication of this unit. The present systematic analysis of the outcrops of this region and similar ones in the sectors of Huesa, Bogarra, Tálave and Cambil indicate, in all cases, that only one unit of carbonates occurs between the Buntsandstein and Keuper beds (Fig. 7).

The arguments supporting our interpretation of a single carbonate unit are:

1. Lithostratigraphic: In all the studied sections of each carbonate interval, the same lithofacies can be recognized and the two members are clearly differentiated.
2. Palaeontological: Similar bivalve assemblages can be recognized in all sections. The ammonoid record also demonstrates the existence of a single carbonate unit, since the same species appear in similar stratigraphic positions. In addition, pollen associations of Carnian age were found in some of the siliciclastic beds situated between the carbonate intervals (Besems 1983), and this was confirmed in the present study (Fig. 8).
3. Structural: Many of the carbonate units disappear laterally over a short distance. Moreover, in most outcrops, the dip of the beds changes rapidly, their thicknesses vary laterally and fault surfaces can be found, and thus it is easy to interpret the bases of these levels as tectonic contacts (Fig. 8). Furthermore, westward-verging faults are visible in the carbonate units in many of the outcrops and also in the type section of the Siles Fm (Fig. 9).

Cehegín Formation

The type area of the Cehegín Fm was established in the zone between Cehegín, Calasparra, Cieza, and Bullas (Fig. 10). In this area, the complete stratigraphy of this formation is characterized basically by a succession of dark

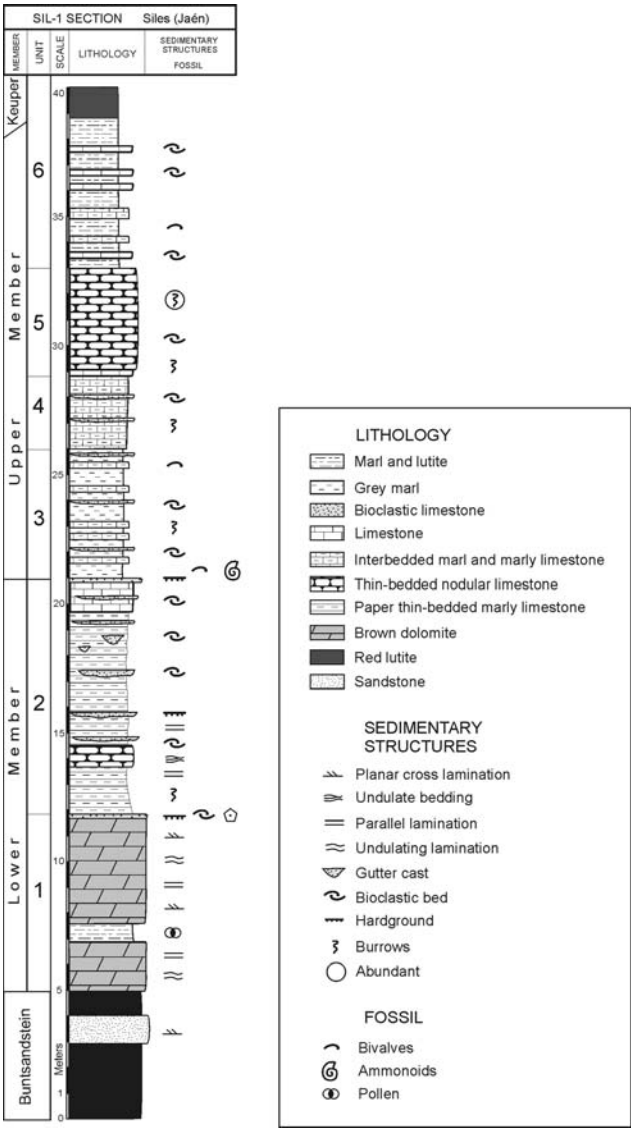


Fig. 6 Stratigraphic log of the Siles Formation holostratotype (SIL-1, Siles section). See Fig. 5 for location

limestones with marly intervals in the upper part. The Cehegín Fm is named after the town of Cehegín, in the north-east of the region of Murcia.

Stratigraphically, the Cehegín Fm is situated on top of red clays and sandstones of the Buntsandstein facies (Pérez-Valera et al. 2000; Pérez-Valera 2005). In all sectors, the Cehegín Fm is overlain by detrital-evaporitic materials of the Keuper facies that belong to the Jaén Keuper Group (Pérez-López 1991).

In the stratigraphic succession of the Cehegín Fm, two main lithological members were differentiated (Figs. 11, 12) and correlated with the two members described in the Siles Fm. The lower member is comprised of two or three laminated carbonate beds with marly-limestone intercalations and storm deposits. The upper member is composed primarily of bioclastic and nodular limestones, bioturbated to a lesser or greater extent (Pérez-López 1997), and intervals of thin-bedded carbonates and marls. The upper part of the sections gradually progresses into the Keuper facies, where gypsum replaces the dolomite.

These lithological features extend to the central sector of the Betic Cordillera (Figs. 13, 14) and thus the Cehegín Fm occurs in the External Zones.

Age of the Cehegín Formation

The carbonates of the Cehegín Fm are rich in bivalves, foraminifers, conodonts, and cephalopods (ammonoids and nautiloids). According to the ammonoid record of the Calasparra section (CL-1), three biozones have been distinguished in 11 successive beds (Pérez-Valera et al. 2005; Pérez-Valera 2005): the Brotzeni Zone, Curionii Zone (divided into the subzones Curionii and Awadi), and the Epigonus Zone.

The type section of the Cehegín Fm (CN-1) and the Arroyo Hurtado section (ARH-1) have a succession of ammonoids similar to that observed in Calasparra, especially in the lower member, although it has still not been completely characterized.

These ammonoid associations belong to the Sephardic Domain and share many taxa with the Sinai Desert and the Negev (Israel). The associations can also be correlated with those of other areas of Spain (Catalonian Coastal Ranges and Island of Minorca) and the Tethys Province (Goy 1995).

Since the IUGS accepted that the GSSP (Global Stratotype Section and Point) boundary was situated at the base of the Curionii Zone (Brack et al. 2005), the lower part of the sections of the Cehegín Fm have been assigned to the Ladinian (base of the Curionii Zone), although the lowermost carbonates could be Anisian in age. *Eoprotrachyceras curionii* first appears at the top of the first bed of laminated limestones, although in the Calasparra Section this species appears at top of the second bed of laminated limestone (Perez-Valera 2005). In the upper part of the Cehegín Fm, all the fauna discovered to date belong to the Ladinian, such that the Ladinian-Carnian boundary should be assigned to the final beds of the Muschelkalk facies or the first detrital-evaporitic rocks of the Keuper facies.

Other fossils found in the Cehegín Fm: bivalves (*Costatoria kiliani, Enantiostreon flabellum, Bakevellia hallensis, Gervillia jouleadi, Pseudocorbula gregaria,* among others), foraminifers (*Lamelliconus cordevolicus, Lamelliconus* gr. *biconvexus-ventroplanus, Triadodiscus eomesozoicus*) and conodonts (*Pseudofurnishius huddlei, Pseudofurnishius murcianus*), are consistent with an age of early to late Ladinian (Márquez-Aliaga 1985; Márquez and Pérez-López 2001; Plasencia 2005, among others).

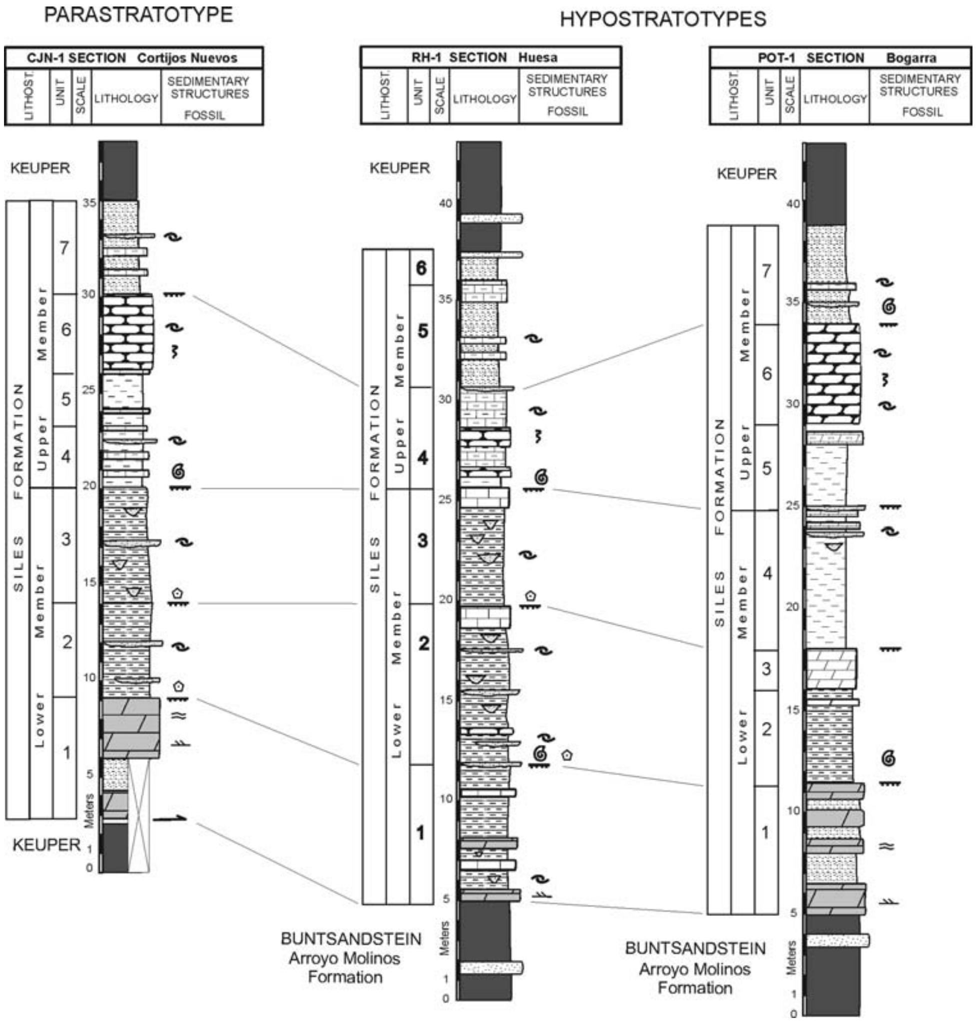


Fig. 7 Stratigraphic logs of the parastratotype (CJN-1) and hypostratotypes (RH-1 and POT-1) for the Siles Formation. Legend as for Fig. 6. The location is provided in Fig. 5

Facies and sedimentary environments

Several significant facies types were distinguished according to lithology, texture, sorting, grain composition, and sedimentary structures (Table 1). Almost all facies types are represented in both formations of the Muschelkalk. However, some facies are exclusive to one formation and others appear at a different frequency in each formation. Also, the thickness of some facies varies from one formation to the other.

Facies of the Siles Formation

Facies 1: Brown dolosparite

A brown mesocrystalline dolomite facies occurs locally in the lower part of the Muschelkalk sections. Bed thicknesses range from 1 to 7 m. Bedding is commonly massive, but some intervals show parallel lamination, wave ripples or trough cross-bedding. Ooids can be recognized in thin sections of megacrystalline dolomite, suggesting an original grainstone texture at some beds (Fig. 15a). Stratigraphically, the dolomite overlies the red lutites and sandstones of the Buntsandstein facies and grades into the upper facies.

Interpretation: Given their cross-bedding and the presence of ooids, these sediments are interpreted as calcarenites deposited under high-energy conditions that were later dolomitised. The position of the dolomite over the Buntsandstein facies indicates it was the first sediment of the transgressive stage and corresponds to very shallow upper shoreface or foreshore deposits (James 1979). Originally, this dolomite was probably like the oolitic sands of Joulters Cays (the Bahamas) or coast of Kuwait, which are interpreted as shallow shoreface and beach sediments related to tidal channels (e.g., Picha 1978; Wright 1984; Boardman and Carney 1991).

Facies 2: Brown dolomicrite

Dolomicrite beds with thin lamination and evaporite moulds occur in the lower part of some sections, although they are not easy to recognize due to dolomitization. This facies is related to the brown dolosparites (Facies 1) but

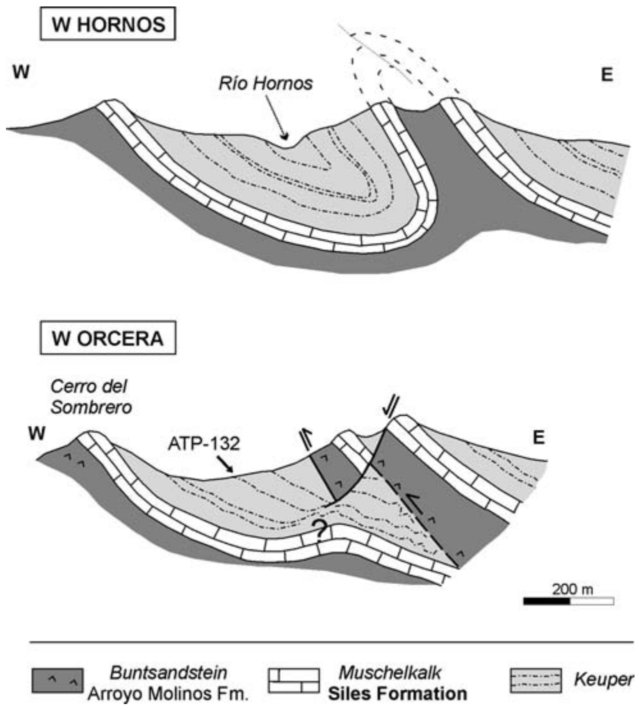


Fig. 8 Geological sections of the Siles Formation rocks, in which it can be seen that the multiplicity of the outcropping carbonate levels of this formation is due to tectonics. ATP-132 (pollen sample): *Patinasporites densus* and *Kuglerina meieri* suggest a Carnian age. In all cases, the carbonate unit is stratigraphically the same

their contacts are not clear due to a massive appearance. In some sections, however, the thickness of thin laminated beds may reach 1–2 m.

Interpretation: This microcrystalline dolomite is interpreted as originally microbial mats due to the undulating thin lamination and evaporite moulds, and thus corresponds to intertidal to supratidal sediments. The features of both brown dolomites are very similar to those of subtidal to intertidal deposits with planar-laminated stromatolites of the Rojals Unit of the Triassic Catalan Basin, NE Spain (Calvet et al. 1990).

Facies 3: Limestone with crinoids

This facies is not common but is significant. It consists of wackestones to grainstones with peloids, bioclasts, usually fragments of molluscs and crinoids, especially in the Siles Fm (Fig. 15b). Locally the facies displays wave ripples on the tops of beds. The thickness of beds ranges from 10 to 30 cm and the facies occurs in the lower member of Muschelkalk carbonate, at the top of some beds. The lower contact grades into the underlying muddy facies and the upper contact is sharply overlain by upper beds of different facies. This facies is partially dolomitized in the Siles section, and has iron-oxide mineralizations and borings on the top. In the Cehegín Fm, there is a similar facies, although the components of the limestone are more variable: bivalves and foraminifers also occur. Moreover, in the Calasparra section, this facies is rich in ooids and shows mineralized iron at the top and contains traces of *Thalassinoides* and *Trypanites*.

Interpretation: This limestone facies, containing wave ripple structures locally, is generally interpreted as sediments deposited in the shoreface. Small sedimentary structures

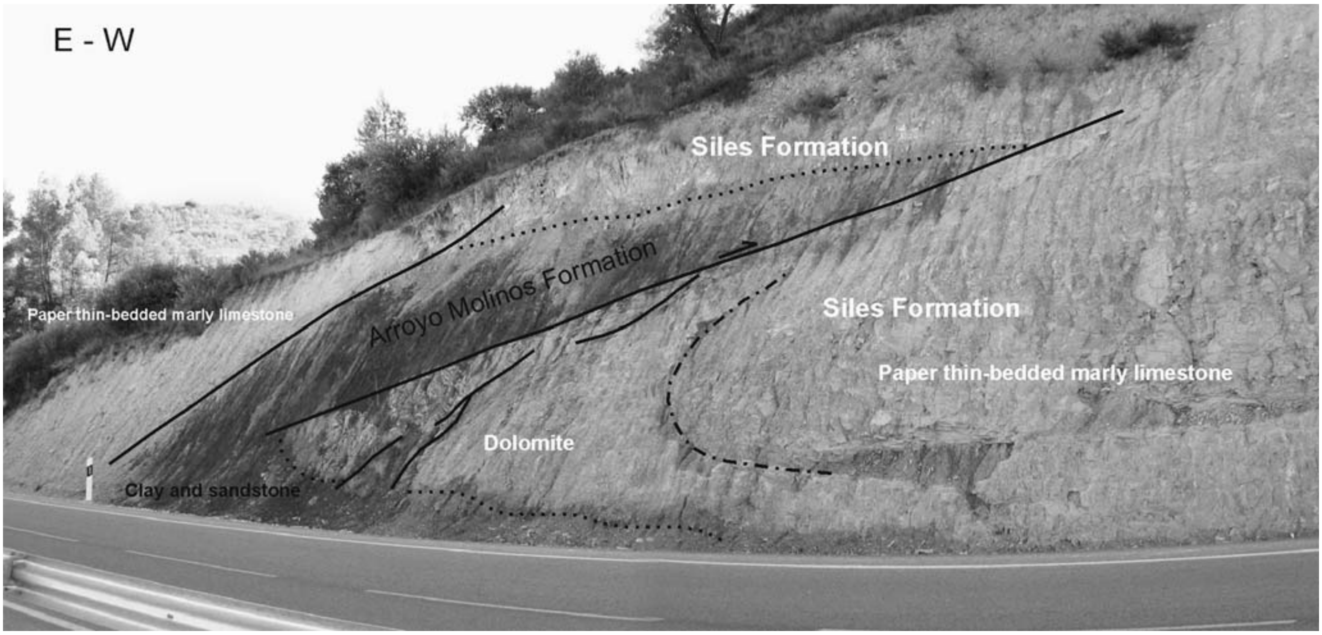


Fig. 9 Talus of the highway between the localities of Siles and Puerta de Segura (Jaén Province), where the Siles Formation carbonate unit is duplicated due to a subhorizontal fault

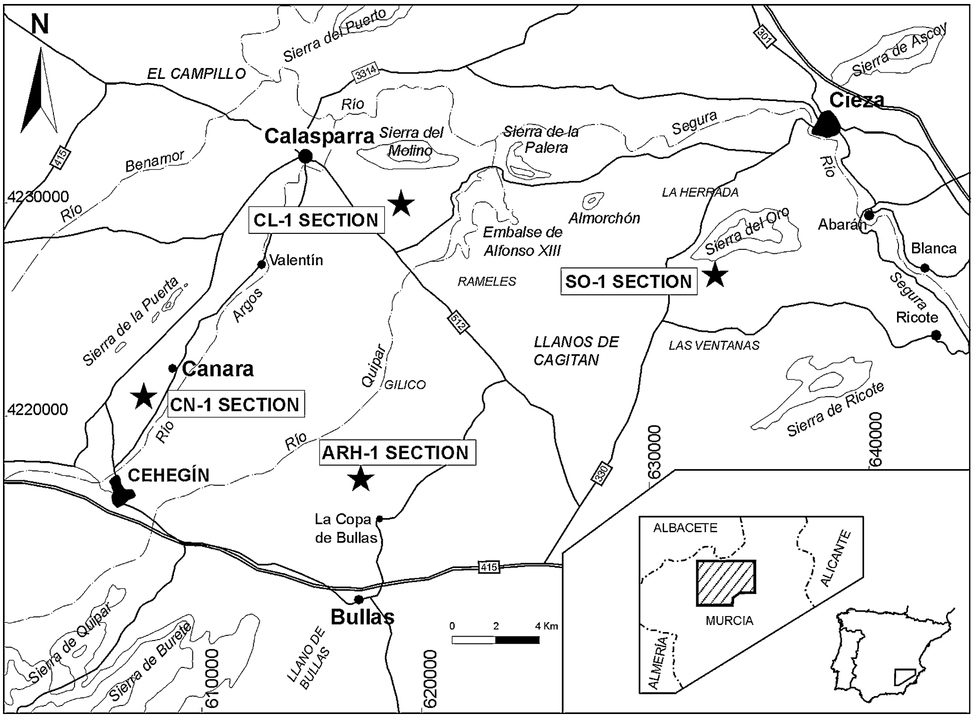


Fig. 10 Geographical location of the main stratigraphic sections of the Cehegín Formation in the Murcia Province (*CN-1*, Canara; *SO-1*, Sierra del Oro; *ARH-1*, Arroyo Hurtado and *CL-1*, Calasparra)

suggest that the wave energy of this platform was moderate. In some cases, the main feature of these wackestones is their position above finer-grained facies and their iron-oxide coating and borings at the top. The latter features are related to a hardground developed on a thin bioclastic bed, when the sea level rose. Accordingly, traces of *Thalassinoides* formed first and *Trypanites* formed later when the seafloor became harder. The hardgrounds were sometimes covered by iron-oxide mineralization (Bertling 1999; Malpas et al. 2005).

Facies 4: Paper-thin bedded marly limestone

This facies consists of mudstones, argillaceous to a greater or lesser extent, and is characterized by paper-thin bedding, although laminae are variable in thickness. Fossils or carbonate grains are usually missing in this lithofacies although bioclastic rudstone interbeds of Facies 5 and 6 occur locally. Paper-thin bedded marly limestone is the most common facies of the Siles Fm and comprises about 30% of the stratigraphic successions of this formation.

Interpretation: Paper-thin bedding formed under low-energy conditions on a lower shoreface to offshore transition zone, below the fair-weather wave base and above the storm wave base constrained by the presence of tempestite beds (see below). Thin lamination, similar to that observed in the shales of the Lower Member of the Volcancito Formation (Esteban 2003), occurs in recent sediments deposited from dilute suspended fine-grained sediment flows, from which silt-sized particles rained down onto the sea floor forming a thin layer, only “a few grains thick” (Esteban 2003). Stanley (1983) proposed a “detached turbid layer” model to explain the thin parallel lamination of fine-grained sediments in the modern Mediterranean. Suspension settling in deeper and quiet offshore water was suggested as the dominant sedimentary process responsible for this fine lamination (O’ Brien 1990). Calvet et al. (1990) interpreted marlstone with paper lamination as distal ramp deposits in a facies association of the Rasquera limestone. In conclusion, this facies is interpreted as fine sediment deposited in an offshore transition zone of an outer ramp, and can be correlated with Facies 12.

Facies 5: Shell-debris limestone

Beds of packstone/floatstone to grainstone/rudstone are intercalated in muddier limestone. These carbonate beds contain bivalves, brachiopods, gastropods, or echinoderm fragments, although ooids, peloids and intraclasts are present in some beds (Fig. 15c). The beds usually have sharp erosive bases and display graded parallel lamination or, for example, cross-lamination or wave ripples such as Kostic and Aigner (2004) described for fine tempestites. This fine limestone, consisting of silty deposits, occurs in some parts of the succession, although the coarser, or shell-debris limestone, is common in the succession overall.

Interpretation: These facies are interpreted as storm deposits of an offshore transition zone. These deposits have the typical features of tempestites (Specht and Brenner 1979; Kreisa 1981; Aigner 1985). The context can vary,

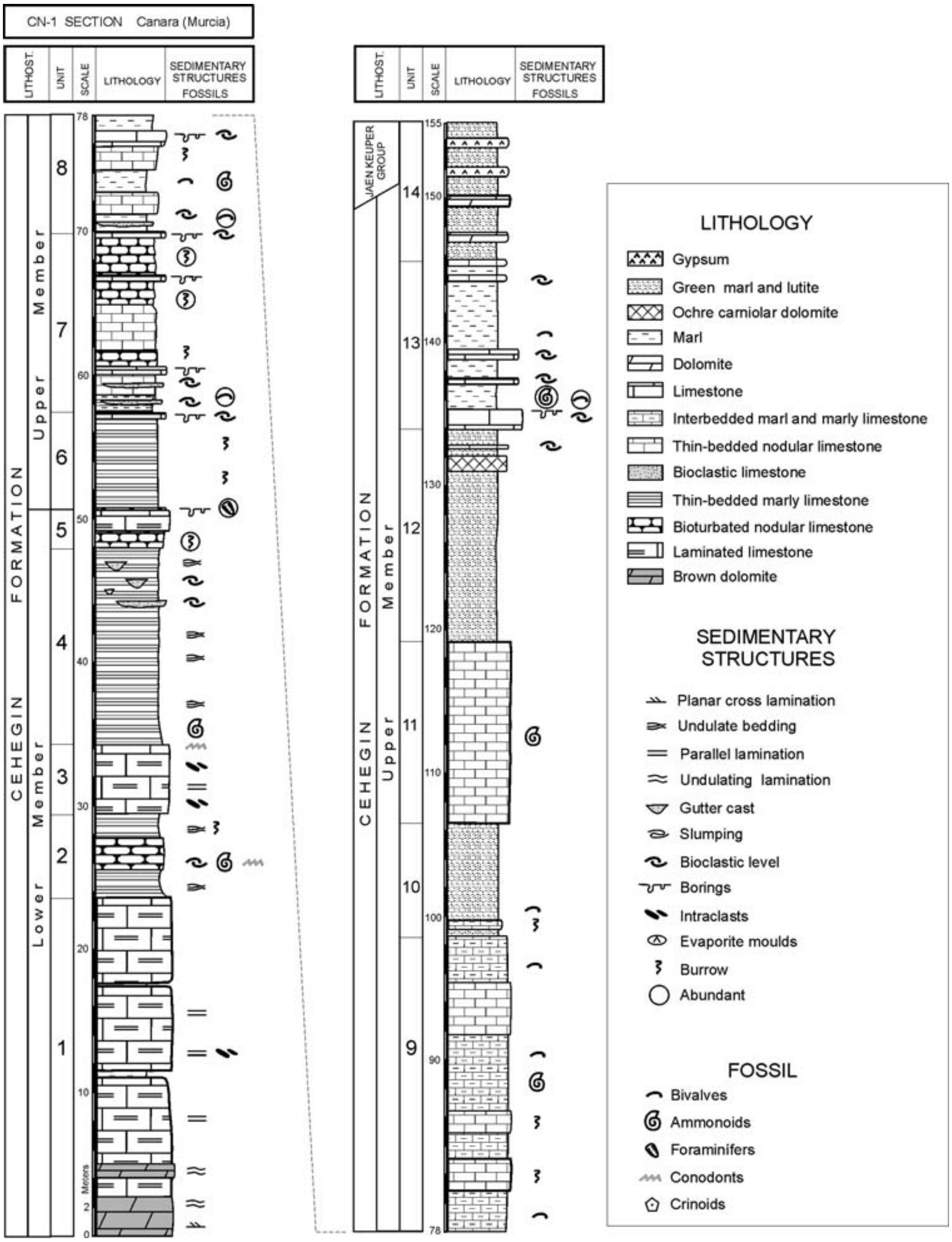


Fig. 11 Stratigraphic log of the Cehegín Formation holostratotype (*CN-1*, Canara section). For location see Fig. 10

although they are always coarse sediments deposited on a muddy platform where the storm current energy began to decrease to allow for deposition, or where bioclasts were concentrated after being winnowed by storm waves.

Facies 6: Gutter casts

In the formations studied, gutter casts and pot casts of variable size occur locally (Aigner and Futterer 1978). The gutter casts are usually filled with normally graded skeletal limestone (rudstone or shell floatstone), although some contain only mud. Normally these structures appear in Facies 4, 7, or 12.

Interpretation: The gutter casts were formed by storms in different environments. In Muschelkalk facies, Pérez-López (2001) interpreted these structures as storm deposits of a bypass zone in a muddy ramp (Myrow 1994). Gutters developed in the very shallow waters of shoreface to offshore transition zones.

Facies 7: Interbedded marl and marly limestone

This facies consists of a rhythmic alternation of marl and marly limestone forming intercalations in a thickness of 0.5–3 m. The marly limestone is usually mudstone but locally wackestone with bioclasts. There are some burrows (*Planolites*) and bivalve and ammonoid shells can be found. Marls are grey with some burrows and are more common in the lower part of this facies. Bioclasts rarely

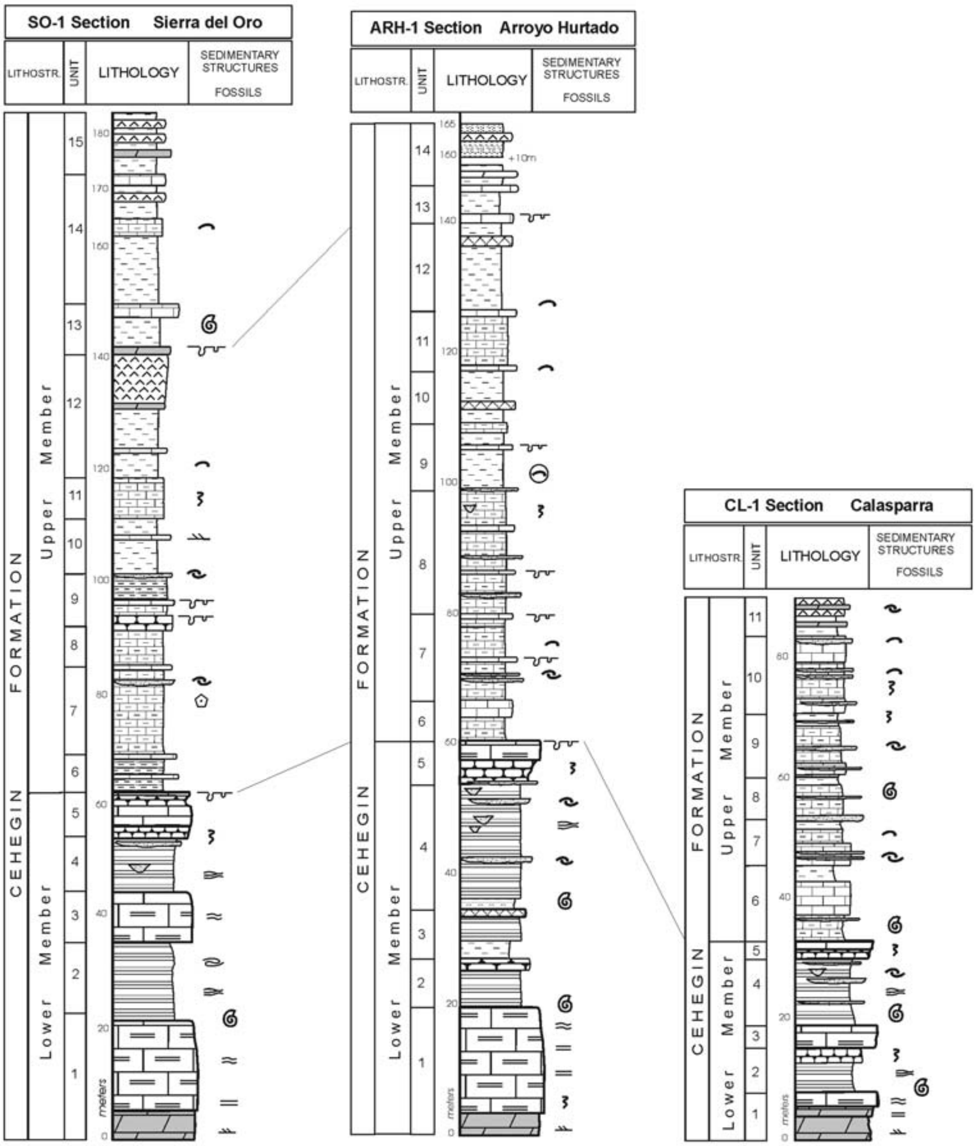


Fig. 12 Stratigraphic logs of the parastratotype (SO-1, ARH-1 and CL-1) for the Cehegín Formation. Legend as for Fig. 11. For location see Fig. 10

appear in these marls. This facies grades into the upper facies, where some shell-debris limestone appears (Facies 5).

Interpretation: This facies was deposited in low-energy conditions in a relatively deep zone, below, or very close to, storm wave base (e.g., Kostic and Aigner 2004). In the Germanic basin, marlstones characterize the deeper depositional areas of the ramp (Aigner 1985; Klein 1985; Schwarz 1985). The presence of ammonoids suggests that the environment was an open ramp where storm waves reached the floor depositing tempestites. This facies is similar to other thin marly limestones of the Muschelkalk facies of the Iberian Peninsula, which have been interpreted as outer ramp deposits (Calvet and Tucker 1988; Calvet et al. 1990). In conclusion, this facies is interpreted as an offshore zone or as an offshore transition zone, when tempestites appear in the facies of an outer ramp.

Facies 8: Thin-bedded nodular limestone

This facies is composed of beds, 5–10 cm thick, normally intercalated with thin marl beds. It consists of wackestones (floatstones) with peloids, gastropods, algae, bivalves and

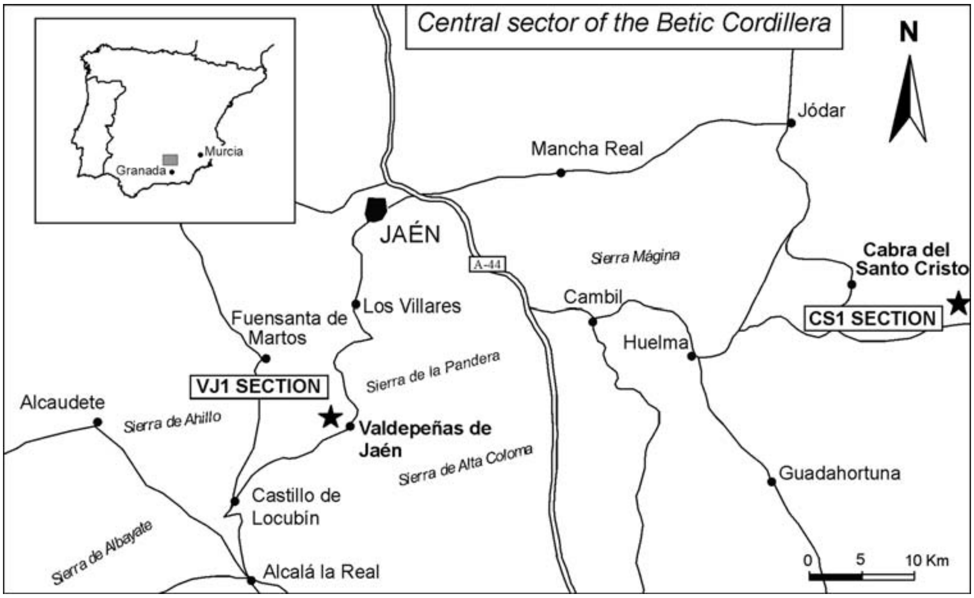


Fig. 13 Geographical location of the hypostratotypes of the Cehegín Formation (CS-1 section of Cabra del Santo Cristo; VJ-1 section of Valdepeñas de Jaén) in the central sector of the Cordillera (Jaén Province)

echinoderms (Fig. 15d). Locally, bivalve shells such as those of *Enantiostreon* appear. The main characteristics of this facies are its nodular texture and presence of considerable bioturbation. In the Cehegín Fm, this same facies may contain some ammonoids. No sedimentary structures related to high energy appear, although some shell-debris limestone intercalations from Facies 5 may be observed.

Interpretation: These fine sediments showing bioturbation and shells are interpreted as protected, lagoonal-type environments of low-energy conditions, that built-up under episodic turbulence below fair-weather wave base (Jank et al. 2006). The presence of ammonoids in facies of the Cehegín Fm suggests an open-platform zone. The nodular texture is the result of a combination of bioturbation and compaction, although bioturbation seems to be the dominant factor for the development of nodularity (e.g., Kennedy 1975; Werner 1986; Clari and Martire 1996). Facies 8 is interpreted as low-energy sediments deposited in a relatively open lagoon setting.

Facies 9: Marl and thin limestone beds with shells

This facies consists of grey or white marls interbedded with thin muddy limestone beds. Gastropods and bivalves are common. Most of the original shells dissolved leaving moulds filled with sparry cement. The most characteristic shells are: *Enantiostreon difforme, Costatoria goldfussi, Bakevellia costata*, and *Gervillia jouleaudi.*

Interpretation: Facies lithology and fauna suggest a low-energy environment related to the nearshore. Some bioclastic thin beds correspond to the high-energy storm deposits of Facies 5. The lithology, bedding, and fossils of this facies are very similar to those of other Triassic outcrops of the Iberian Peninsula (Pérez-Arlucea 1991; Pérez-López et al. 1991; Márquez-Aliaga and Ros 2003). They are interpreted as very shallow-marine sediments, deposited under lagoon-like conditions.

Facies of the Cehegín Formation

This formation displays the same facies as the Siles Formation, although their thicknesses vary and Facies 4 (paper-thin bedded marly limestone) is absent or very rare in the Cehegín Formation. The formation also has certain features that are exclusive to it (Table 1):

Facies10: Laminated limestone

This facies is composed of very thickly bedded (>2 m) laminated grey limestone, which is locally bioturbated. The facies displays parallel lamination and locally shows small wave ripples. It consists of mudstones (microsparite) with a few small bivalve skeletal grains or foraminifers of *Nodosaria ordinata* Trifonova (Fig. 15e). In some cases, intraformational conglomerate beds (15–35% of the laminated limestone facies) up to 10 cm thick appear. These contain micritic clasts of lithified carbonate sediment (mud chips). This facies grades into the overlying one, which is normally Facies 3.

Interpretation: The thin micritic limestone laminae are in some cases interpreted as being microbial in origin, since it is locally characterized by an irregular undulated lamination, resembling small stromatolite domes. However, the laminated limestones normally contain thin to thick beds of calcisiltite derived microsparite, displaying current sedimentary structures. The microsparite might have originated from recrystallization during the diagenesis of silt-sized carbonate grains such as calcispheres or peloids (Duringer

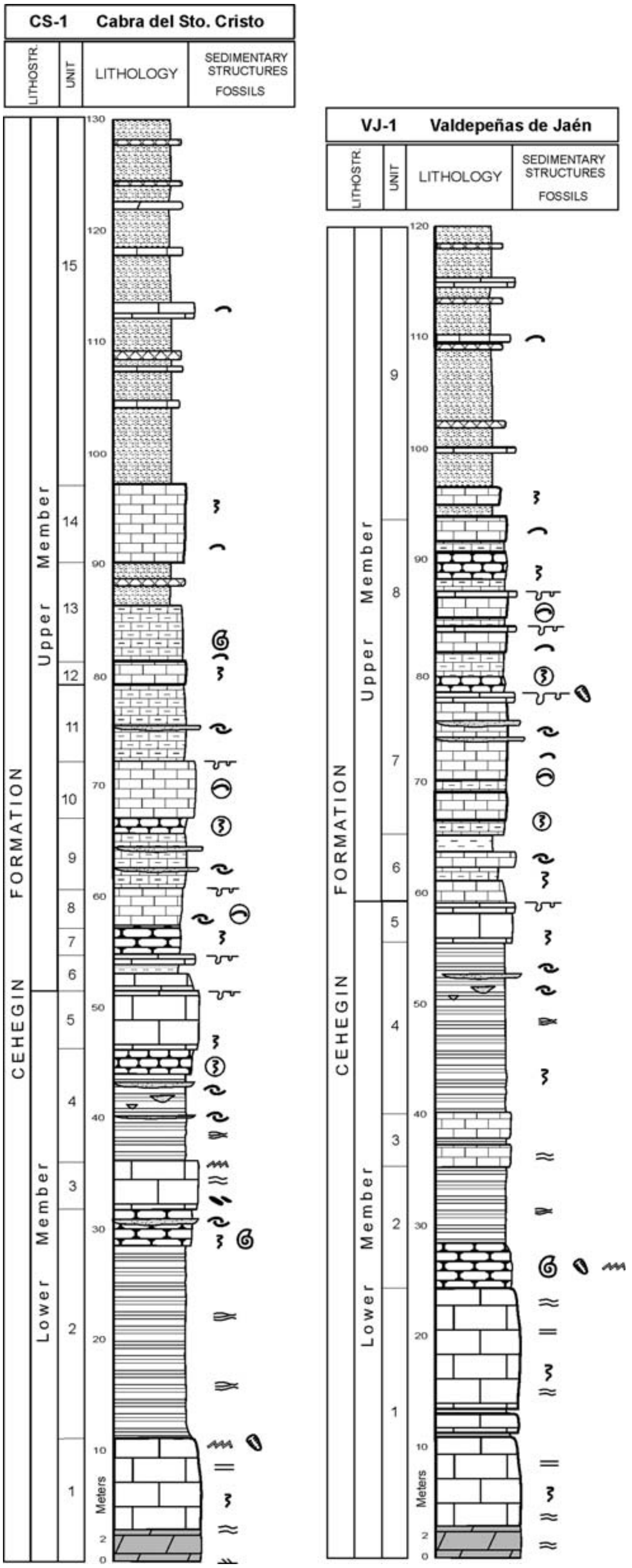


Fig. 14 Stratigraphic logs of the hypostratotype (CS-1 and VJ-1 sections) for the Cehegín Formation. These logs from the Jaén Province show equivalent features to the different sections from the Murcia Province (Figs. 11 and 12). Legend as for Fig. 11. For location see Fig. 13

and Vecsei 1998; Vecsei and Duringer 1998). The interpretation of the relatively high energy of these deposits is locally supported by the presence of *Diplocraterion* burrows. These facies are interpreted to indicate deposition in a very shallow nearshore zone, from subtidal to intertidal zones. The available sediment was fine and locally made up of cohesive laminated sediment (Pérez-López 2001). In its context, this facies may be interpreted as mudbank sediments (e.g., Enos and Perkins 1979; Wanless and Tagett 1989).

Facies 11: Bioturbated nodular limestone

Typical levels have a distinctive bioturbation texture. These levels are grey muddy limestone with a homogeneous and generally massive appearance. The original texture of the fine sediment has been completely destroyed by bioturbation such that it resembles breccia. Most of the burrows identified in this facies are horizontal *Planolites*. Thin bioclastic beds rarely occur in this facies. It shows gradual transition towards other facies.

Interpretation: This facies reflects slow and continuous sedimentation under low-energy and oxygenated conditions, and in places where bioturbation is moderate, it is possible to interpret the sediments as subtidal deposits of tidal flats (Shinn 1983). However, in the stratigraphic succession, this facies appears in different contexts and may also be interpreted as an outer shoreface zone, where wave energy was very low except when there were storms (Pérez-López 2001). Thus, the facies can be interpreted as outer ramp deposits, although when related to Facies 10, it is interpreted as a restricted shallow subtidal environment.

Facies 12: Thin-bedded marly limestone and marl

The thin-bedded marly limestone facies contains interbeds (each bed is 1–5 cm thick) of grey limestone, marly-limestone, and white marl. Grain sizes for the grey limestone and carbonate portions of the marly limestone correspond to mud or silt, now microsparite. Sedimentary structures in the thin-bedded calcisiltite include parallel, undulating lamination and tabular cross-bedding. Some small slumps occur. A number of Ceratites and scattered bivalve shells occur parallel to the bedding and, in rare cases, form a parting lineation.

Interpretation: The undulating, flaser-like appearance of beds in vertical sections is the result of their small, almost symmetrical ripples. The cross-bedding corresponds to channel-filling lateral-accretion bedding (Fig. 4), interpreted by Duringer and Vecsei (1998) as being typical of subtidal deposits. According to these authors, such channels are likely to be of tidal origin and the simultaneous occurrence of small wave-ripples and channel-filling

Table 1 Classification and description of the facies

Facies number	Facies name	Microfacies texture	Main components	Interpretation	Siles Formation[a]	Cehegín Formation[a]
1	Brown dolosparite	Mesocrystalline dolomite	“Ghosts” of ooids	Shallow subtidal and intertidal channels	c	c
2	Brown dolomicrite	Microcrystalline dolomite	Stromatolite lamination	Intertidal to supratidal	r	c
3	Limestone with crinoids	Wackestone-packstone (grainstone)	Peloids, bivalves, gastropods, crinoids	Shoreface	r	r
4	Paper-thin bedded marly limestone	Mudstone	–	Shoreface to offshore transition zone	a	vr
5	Shell debris limestone	Floatstone-rudstone and packstone-grainstone	Shell debris, bivalves, brachiopods, gastropods, peloids	Offshore transition zone	c	c
6	Gutter casts	Floatstone-rudstone and packstone-grainstone	Shell debris, bivalves, brachiopods, gastropods, peloids	Shoreface to offshore transition zone	c	c
7	Interbedded marl and marly limestone	Mudstone	Ammonoid shells	Offshore to offshore transition zone	c	c
8	Thin-bedded nodular limestone	Wackestone	Bivalves, gastropods, crinoids, foraminifers	Lagoon conditions	c	c
9	Marl and thin limestone beds with shells	Mudstone and floatstone	Bivalves	Lagoon conditions	c	c
10	Laminated limestone	Mudstone	Bivalves, stromatolites, intraclasts	Intertidal (mudbank)	abs	a
11	Bioturbated nodular limestone	Mudstone	–	Restricted subtidal environment	r	c
12	Thin-bedded marly limestone	Mudstone	Bivalves, ammonoid shells	Offshore to shoreface	r	a
13	Bioclastic limestone with Thalassinoides	Packstone-grainstone	Bivalves, gastropods, peloids, intraclast, algae, foraminifers	Lagoon conditions	abs	a
14	Marl and ochre dolomite	Dolomicrite	Bivalve shells	Intertidal with ponds and lagoon zone	r	c

[a] Presence in the formations

a abundant; *vc* very common; *c* common; *r* rare; *vr* very rare; *abs* absent

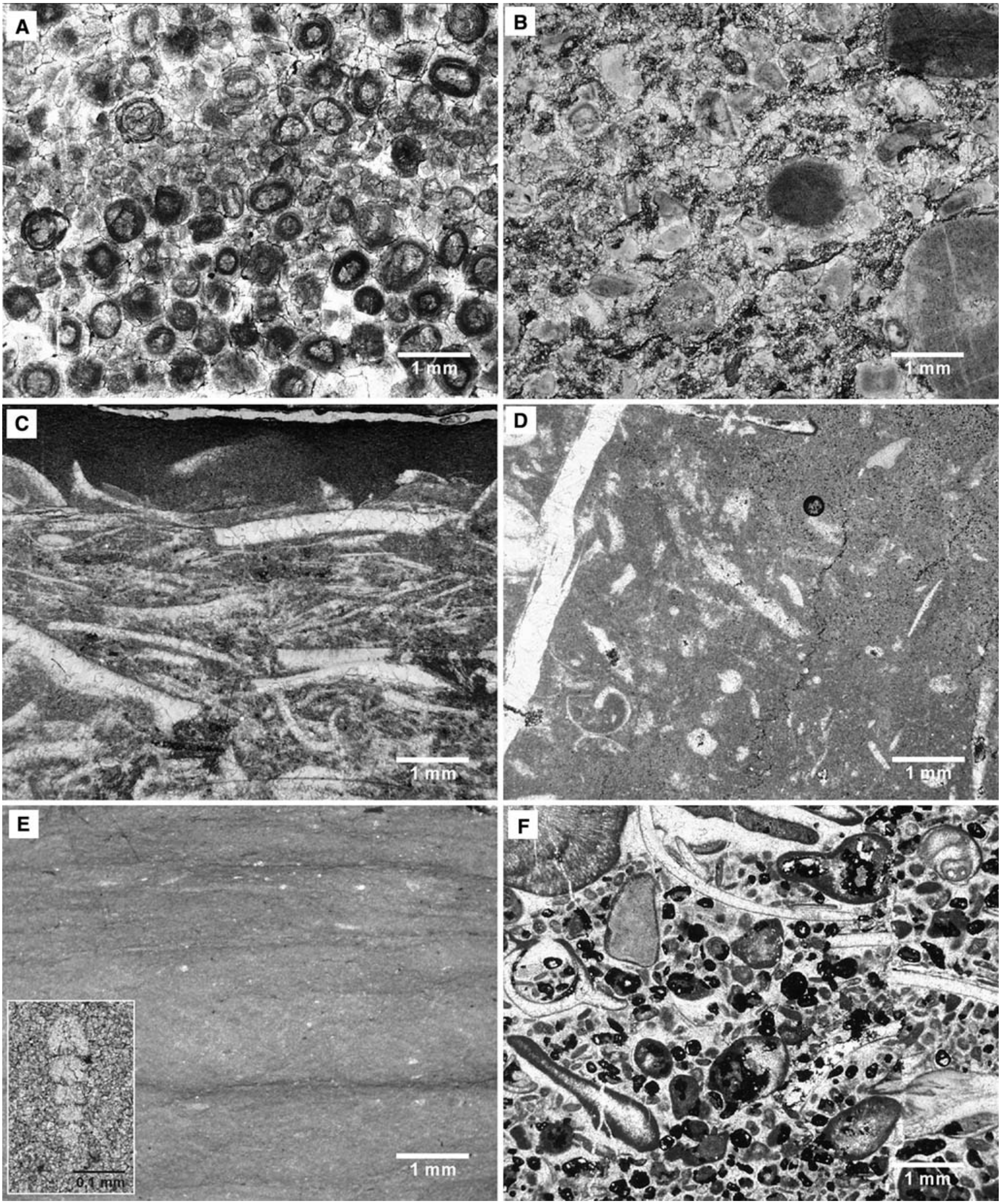
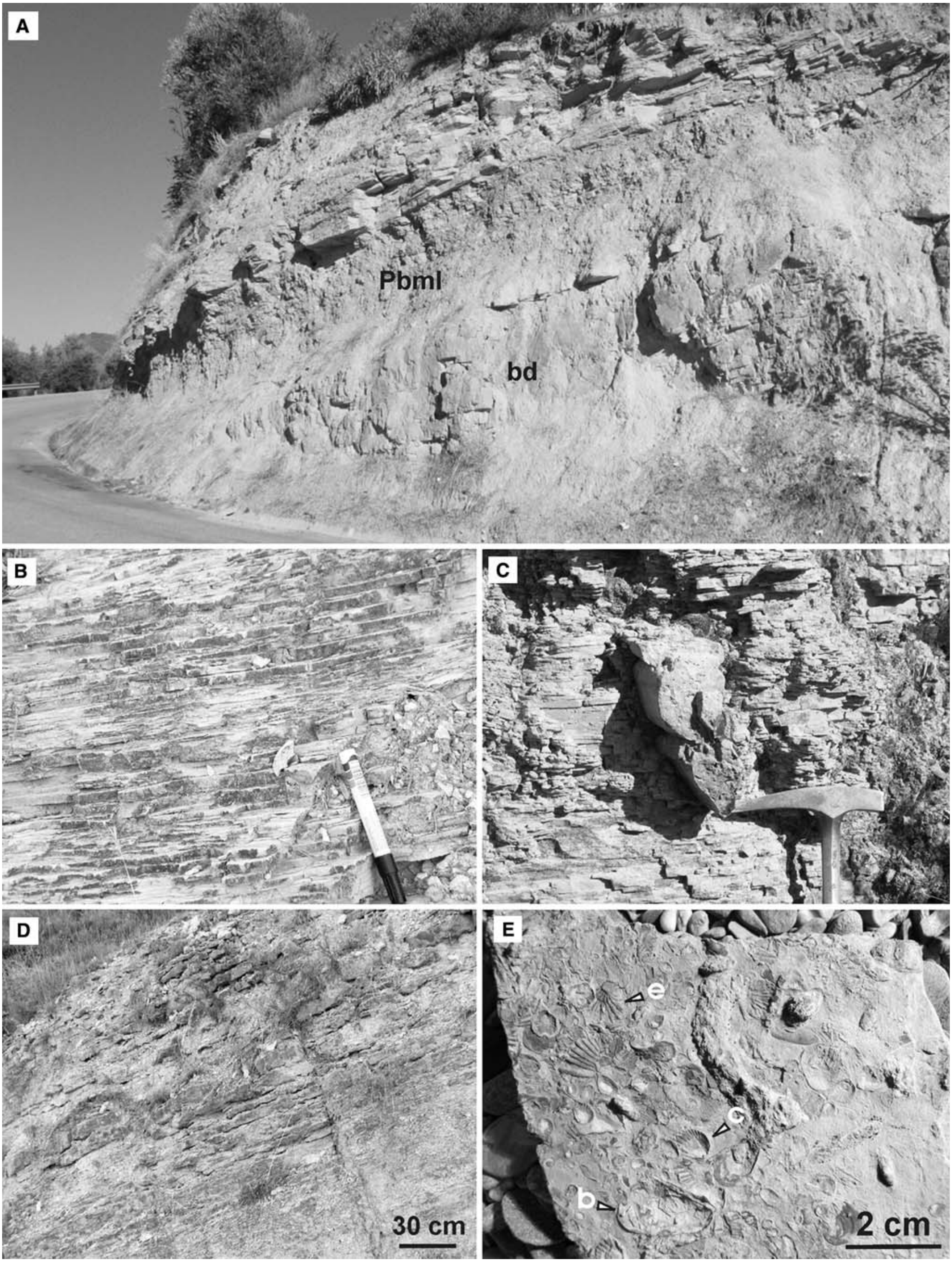


Fig. 15 Plate showing the most significant microfacies related to the described main facies of the Muschelkalk carbonates. **a** Oolitic grainstone that corresponds to dolosparites in the outcrops (Facies 1). **b** Partially dolomitized limestone of a packstone to grainstone origin containing crinoids (Facies 3). **c** Shell packstone interpreted as the shell debris of a graded tempestite, characterized by fragmented bivalves and brachiopods. Mud deposited at the top (Facies 5). **d** Wackestone with fragmented bivalves, gastropods, crinoids (Facies 8). **e** Laminated mudstone (Facies 10) locally showing skeletal grains like *Nodosaria ordinata* Trifonova (see enlarged photograph). **f** Grainstone containing fragmented shells with micritic envelopes, peloids and intraclasts. The skeletal grains are bivalves, gastropods, crinoids and algae (Facies 13)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◀ **Fig. 16** Facies and main features of the Siles Formation sections. **a** Outcrop of the lowermost part of the Cortijos Nuevos section (*CJN-1*). Note the brown dolomite (*bd*) and paper-thin bedded marly limestone facies (*Pbml*). **b** Detail of the paper-thin bedded marly limestone facies of the lower member (Siles section, *SIL-1*). **c** Another detail of the thin-laminated marly limestone but in this case the facies is more marly, and there is a bioclastic fill (gutter cast). **d** Appearance of the thin-bedded nodular limestone facies (Facies 8) of the upper member (Siles section, SIL-1). **e** Close-up of a typical Facies 9 (marl and thin limestone beds with shells) sample showing the shells found in the upper member of this formation (Cortijos Nuevos section, CJN-1). e *Enantiostreon difforme;* c *Costatoria goldfussi;* b *Bakevellia costata*

lateral-accretion bedding is clear evidence of a very shallow-subtidal setting. Decimetre-scale, undulating erosion surfaces are more common in these facies due to the influence of oscillatory currents on the sea floor. Ammonoids point to an open-marine influence, and the slumps are related to a deeper zone, or slope environment. This facies includes many variations related to sediments deposited in offshore to shoreface environments during a transgression stage, such as Facies 4 of the Siles Formation, when the epicontinental platform had a ramp profile towards the shoreline (Pérez-López 2001).

Facies 13: Bioclastic limestone with Thalassinoides

The thickness of this facies is variable from 0.15 to 5 m, with beds measuring 15–60 cm. These do not show a homogeneous microfacies. They consist of wackestones to grainstones with bioclasts of bivalves and gastropods. At the top of these beds, green alga fragments and *Thalassinoides* burrows, filled with yellow ferroan dolomite, are common, and there are more peloids, mollusc shells and fragmented *Codiacea* algae (packstones to grainstones, Fig. 15f). The facies consists of graded bedding that is coarser towards the top, where bioclastic grainstone appears. An erosion surface with vertical burrows also occurs at the top. In some undulated beds that locally display cross-lamination, shells accumulated in an irregular manner at the top.

Interpretation: This facies is interpreted as shallow-water deposits in which overall energy increased upwards through the beds. The presence of bivalves, green algae, and gastropods is related to shallow water and with wave influence due to the irregular accumulation of shells and some undulated tops. Jank et al. (2006) have related the *Thalassinoides* to a recent organism that lives in intertidal to shallow-subtidal lime mud in lagoons in tropical areas. The burrows commonly remain open and are subsequently filled with coarser grained sediments, which could have been associated with storm events or the downward shift in sea level (Handford and Loucks 1993). In conclusion, this facies is interpreted as shallow-water sediments deposited in relatively low-energy conditions, where waves occasionally influenced the deposits. However, these sediments frequently formed small bioclastic shoals due to aggradation of the deposits.

Facies 14: Ochre dolomite and marl

This facies is composed mainly of thin ochre dolomite beds and green marls. It consists of mudstones, although many shells appear at the top of some thin beds such as *Pseudocorbula gregaria, Gervilla joleaudi*, and *Lingula* sp., which are common in the Muschelkalk of the Iberian Peninsula (Marquez-Aliaga and García Gil 1991; Márquez-Aliaga and Ros 2003). Porosity became high in this facies owing to gypsum moulds. Dolomite intraclasts and mud-cracks occur. This facies also displays thin gypsum beds or cargneules with lutite intercalations.

Interpretation: This lithology and sedimentary structures are interpreted as intertidal deposits overall. The intraclasts and mud-cracks are related to supratidal exposure (Pratt and James 1986) and the gypsum beds indicate evaporative arid conditions.

Facies associations in the Siles Formation

The lower part of the Siles Fm is made up of Facies 1 and 2, brown dolomites with lamination or cross bedding (Facies 1; Fig. 16a). At the top of Facies 1, a bioclastic bed of Facies 3 containing fragmented bivalves and crinoids can be recognized. This association is interpreted as a deepening-upwards sequence, where the mud and ooid sands of the subtidal/intertidal belt pass to skeletal wackestones of the shoreface zone (Facies 3).

The overlying skeletal wackestones display the typical paper-thin bedding of Facies 4 (Fig. 16b), in which interbeds of shell debris limestone (Facies 5) and gutter cast facies (Facies 6) are common (Fig. 16c). At the top of Facies 4, there is a 3–5 cm-thick crinoidal bed, again showing the characteristics of Facies 3. Offshore transition zone deposits pass to the shoreface zone, such that this association of facies (Facies 4-3) is interpreted as a shallowing-upwards sequence.

In all the sections of the Siles Fm examined, two sequences were identified related to Facies 4 and 3 (Fig. 17). An iron-oxide horizon on the top of Facies 3, which was interpreted as a hardground and discontinuity, developed during a transgressive stage. In the Siles Fm, this hardground corresponds to the boundary between the lower and upper lithostratigraphic member (Figs. 6, 7). Up until this discontinuity, lamination in the limestone in general is very common.

Overlying the discontinuity of the lower member, Facies 7 appears (Fig. 17). The lower part of this facies

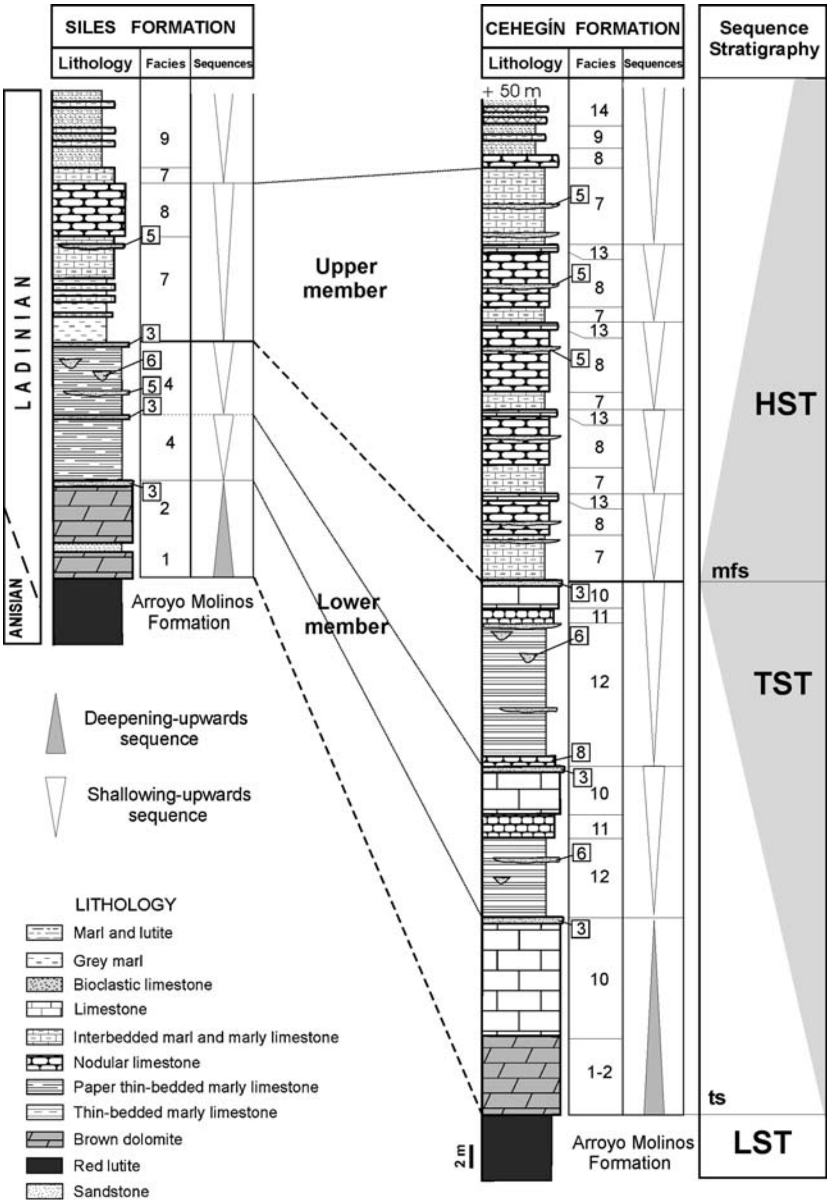


Fig. 17 Standard stratigraphical sections of the two formations characterizing the Muschelkalk facies of the External Zones (Betic Cordillera). Correlation based on lithologic characteristics and fossil contents. Facies, sequences and the sequence stratigraphic framework are indicated. *HST* highstand systems tract; *TST* transgressive systems tract; *LST* lowstand systems tract; *mfs* maximum flooding surface; *ts* transgressive surface

corresponds to a marl interval, whose fossil content is scant, although some ammonoids and bivalves could be discerned. Some bioturbated beds are also present. In the upper portion of this facies, the marls disappear progressively and pass to Facies 8 (Fig. 16d), a nodular limestone interval with intercalations of shell-debris limestone (Facies 5). The first marly sediments of Facies 7 correspond to the offshore zone and were deposited beneath the storm wave base. The second marly limestone sediments, which are of Facies 8, are interpreted as shallower and include more storm thin-beds (Facies 5) and shells. In this facies, the degree of bioturbation increases. This facies is characteristic of the upper member of the Siles Fm.

Above Facies 8, a discontinuity can be observed in several sections (e.g. Siles, Bogarra) along with the development of thin iron crusts on top of the thin-bedded nodular limestones. Above this discontinuity, thin levels of Facies 7 are visible, which represent the last transgressive sediments. Over these sediments are the scarce skeletal beds of Facies 9 (Fig. 16e) and some dolomite levels. This facies changes upwards to the red clays of the coastal Keuper facies. This facies association (Facies 7–9) corresponds to a shallowing-upwards sequence, whose last deposits are coastal sediments.

Facies associations in the Cehegín Formation

As in the Siles Fm, the first deposits of the Cehegín Fm overlying the siliciclastic sediments of the Buntsandstein facies, are Facies 1 and 2, or brown dolomites of intertidal through shallow-marine environments. Over these deposits, appears the laminated limestone of Facies 10 (Fig. 18a) with Facies 3 at the top. Facies 10 passes gradually to a thin, 10-cm-thick interval of Facies 3. These first deposits are interpreted as a deepening-upwards succession.

Facies 10 is repeated in the succession, although it is preceded by Facies 12 or locally by Facies 11 (Figs. 17, 18b). Normally, over Facies 12 containing storm deposits (Fig. 18c), Facies 10 appears, which may pass laterally to the bioturbated Facies 11 (Fig. 18d). In the Calasparra section at the end of this sequence, oolitic packstones to grainstones occur, which suggest a relationship with Facies 3. Offshore transition zone deposits with tempestites pass to the upper shoreface with an intertidal mudbank complex. This complex is composed of microbial mats, mud chips, silts with current lamination (Facies 10) and bioturbed mud (Facies 11). This facies association (Facies 12-11-10) occurs three times in the lower member of the Cehegín Fm (Fig. 18e) and is interpreted as two shallowing-upward cycles (Fig. 17).

Overlying the upper cycle of Facies 12-11-10 (Fig. 17) is a substantial discontinuity characterized by boring in a hardground substrate with iron mineralizations. This discontinuity marks the boundary between the two members of the Cehegín Fm, and represents a change in facies associations. As in the Siles Fm, below this discontinuity, in the lower member, sediments that are generally laminated occur, whereas above this discontinuity marly sediments and shells are more abundant.

The stratigraphic succession of the upper member of the Cehegín Fm is more variable than the lower one and a detailed correlation between the different studied sections is difficult. In the main sections, the upper member is characterized by alternations of the marls and marly limestones of Facies 7 (Fig. 19a). The lower part of Facies 7 is abundant in cephalopods (ammonoids and nautiloids) and bivalves. In some outcrops, this facies also contains *Planolites* and *Chondrites*. These variations are interpreted as different subenvironments of the platform. *Chondrites* are related to shallow low-energy environments with less oxygen (Bromley and Ekdale 1984; Valenzuela et al. 1986). This upper member is mostly characterized by facies association 7-8-13 (Fig. 17). The nodular facies (Facies 8) is common in some outcrops, which grade into bioclastic limestone with *Thalassinoides* (Facies 13). Some tempestites (Facies 5) occur in facies 7 and 8, although in the Calasparra section the presence of tempestites in Facies 8 is considerable (Fig. 19b–d).

This facies association corresponds to shallowing-upward cycles that locally end on an erosion surface, where peloids, bioclasts and shells are concentrated (Facies 13). Facies 13 consists of calcarenitic shoal deposits and thus the facies association is interpreted as a shoaling-upwards sequence. Some studied sections have only one or two thin cycles, although the Cabra Sto. Cristo section (Fig. 14) has four cycles as illustrated in Fig. 17. These shoals did not form a great barrier due to their thin nature, less than 1 m, and they only appear in some sections, although they could have produced a decrease in wave energy towards the coast. For this reason, this high-energy facies is not present in the upper member of the Siles Fm, which consists of finer sediments.

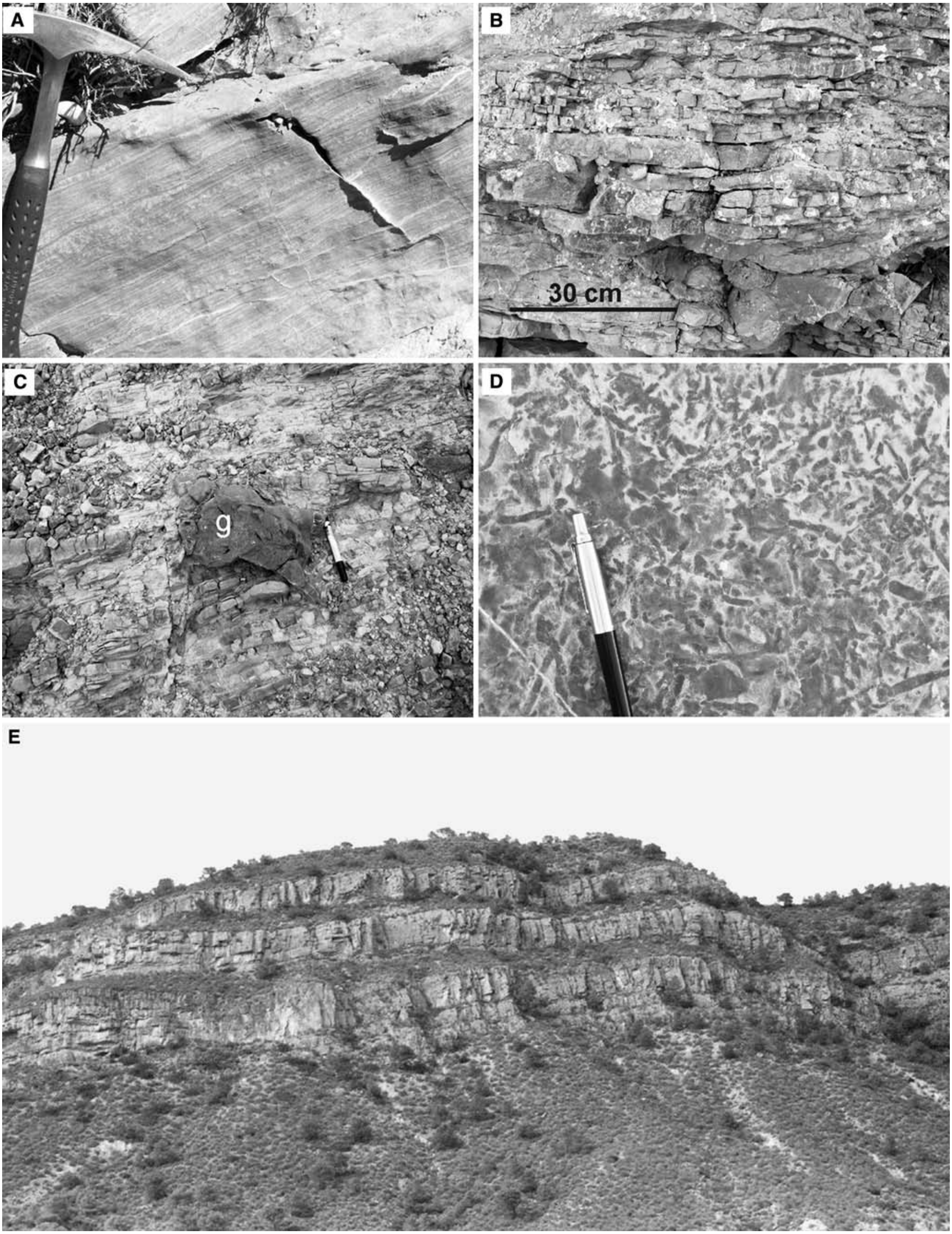
In the uppermost part of the Cehegín Fm, facies of green and ochre lutites together with cargneules and gypsum beds (Facies 14) are the best represented. Obviously, this latter facies was deposited in the shallowest environment. Nevertheless, Facies 8 containing marine fossils is still intercalated in coastal sediments in the transition to the Keuper facies. Facies 9, whose beds are very thin, is also present and often contains a bivalve fauna dominated by opportunistic species that colonized very restricted environments of varying salinity (e.g. *Pseudocorbula gregaria*). This facies association (Facies 8-9-14) represents a shallowing-upwards succession, although some transgressive events occurred.

Sedimentary model and discussion

The carbonate deposits of the Siles and Cehegín Formations can be interpreted as the typical sediments of an epicontinental platform (Pérez-López 1998). The epicontinental or epeiric platform is a very extensive, relatively flat cratonic area covered by shallow sea. This paper tries to emphasize that along the margin of this platform, there may be a gentle slope into the adjoining basin, but the margin is not a major feature of the platform (Tucker 2001).

The Muschelkalk carbonates laterally show the great development of dolomites and limestones, containing microbial laminations with evaporite moulds, bioturbated marly limestones, limestones with abundant bivalves and gastropods, ochre lutites with cargneules and evaporite beds. The evolution of these Muschelkalk carbonates can be interpreted in detail owing to the changes in depositional systems (Fig. 20).

Two members can be distinguished in both formations according to variations in lithology and facies associations. The uppermost facies show the greatest variation while the features and thickness of the lowermost facies are rather constant, indicating greater lateral changes of the environments towards the top of these formations related to shallower facies. The system in general represents the progradation of a lagoon-mud flat complex towards a storm-dominated deeper-water zone, with a ramp profile in its initial stages.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◀ **Fig. 18** Facies and features of the lower member of the Cehegín Formation. **a** Detail of the laminated limestone facies (Facies 10) showing lamination (microbial mat) and thin beds of mud chips (Canara section, CN-1). **b** Appearance of the thin-bedded marly limestone facies (Facies 12). The undulating, flaser-like appearance of the beds in vertical section is produced by the small and almost symmetrical ripples (Cabra del Santo Cristo section, CS-1). **c** Complex gutter cast (*g*) with an asymmetrical cross-section in the thin-bedded marly limestone facies (Calasparra section, CL-1). Marker pen is 14 cm long. **d** Close-up of the bioturbation characteristic of this formation (Facies 11: bioturbated nodular limestone). This facies corresponds to the general "facies of *fucoids*" (Calasparra section, CL-1). **e** Landscape of Sierra del Oro (SO-1 section) where the three typical thick beds of the lower member's laminated limestones are clearly visible

The lower member sediments of the Siles and Cehegín Fms were deposited on a gentle slope (ramp-like) of an epeiric carbonate platform, with notable storm influence. These sediments display some slump structures in Facies 12, whereas they do not appear in the upper member. Oolitic sands and microbial sediments (brown dolomites of Facies 1 and 2), located at the base of the Siles and Cehegín Fms are indicative of the first marine deposits in nearshore zones during the main transgressive stage (Fig. 20a). Subsequent to these deposits, a huge mudbank system developed in intertidal environments, represented in the Cehegín Fm by laminated limestone (Facies 10). The lateral transition from laminated limestone (Facies 10) to bioturbated limestone (Facies 11) to form an intertidal belt or mudbank complex (Fig. 20b) is common. This mudbank complex could have delineated an inner restricted zone, as suggested by Fairchild and Herrington (1989) for the Late Vendian of East Greenland, who described a shoreface-lagoon-peritidal flat. These authors proposed a shore-lagoon model in which muddy coastal and lagoonal carbonate facies are not bound seaward by a continuous reef or sandbody. This is indicative of low wave energy, except during storms, and a low tidal range, so that strong tidal currents only developed

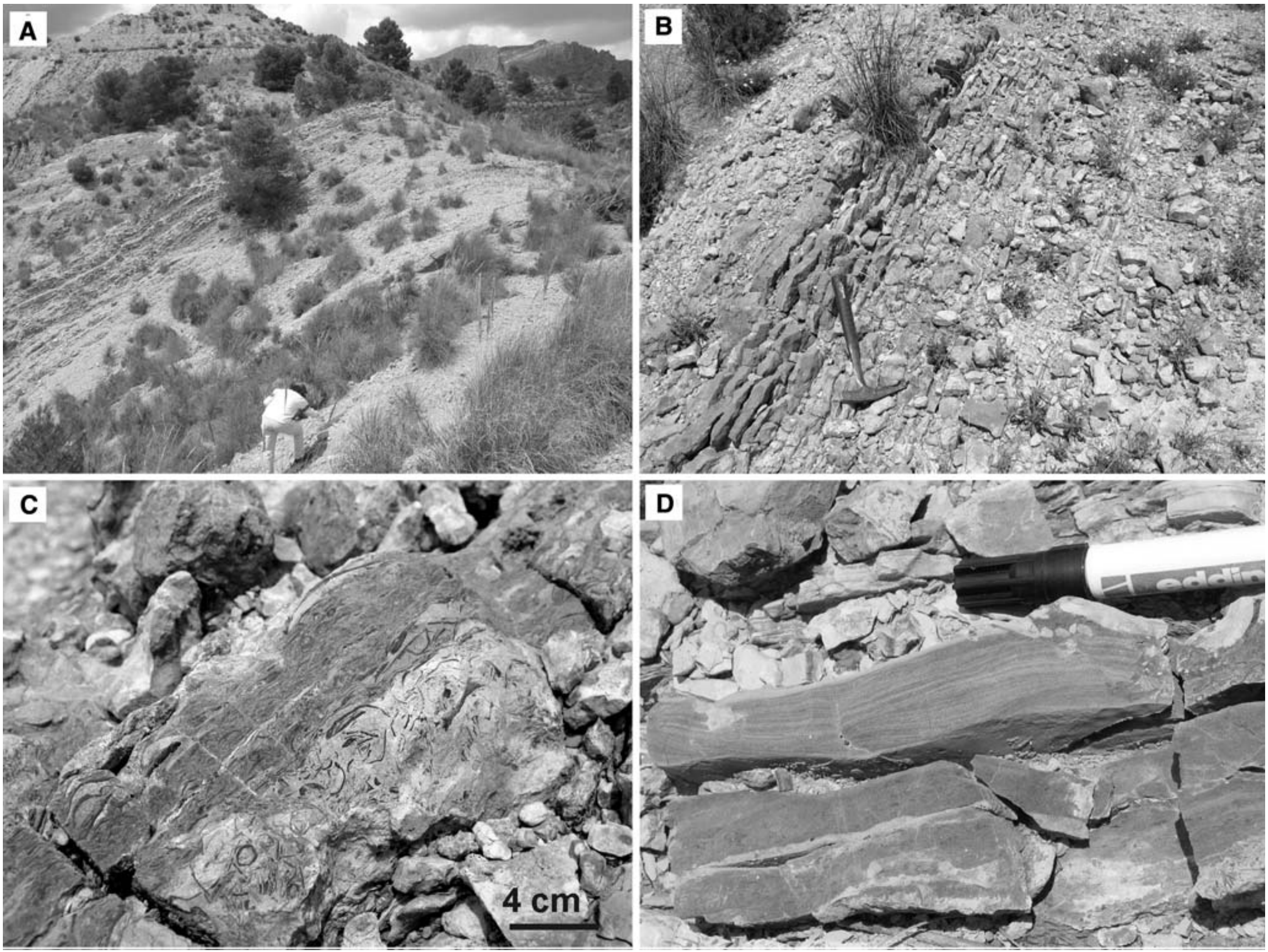

Fig. 19 Lithofacies of the upper member of the Cehegín Formation (Calasparra Section, CL-1). **a** View of the middle part of the upper member: interbedded marl and marly limestone (Facies 7) and some bioturbated nodular limestone (Facies 11). **b** Close-up of the bioturbated nodular limestone with tempestite intercalations (Facies 11 and 5). **c** Detail of a graded tempestite bed (Facies 5) showing large bivalve sections (Calasparra section). **d** Thin silty tempestite bed with wave ripples and mud on top

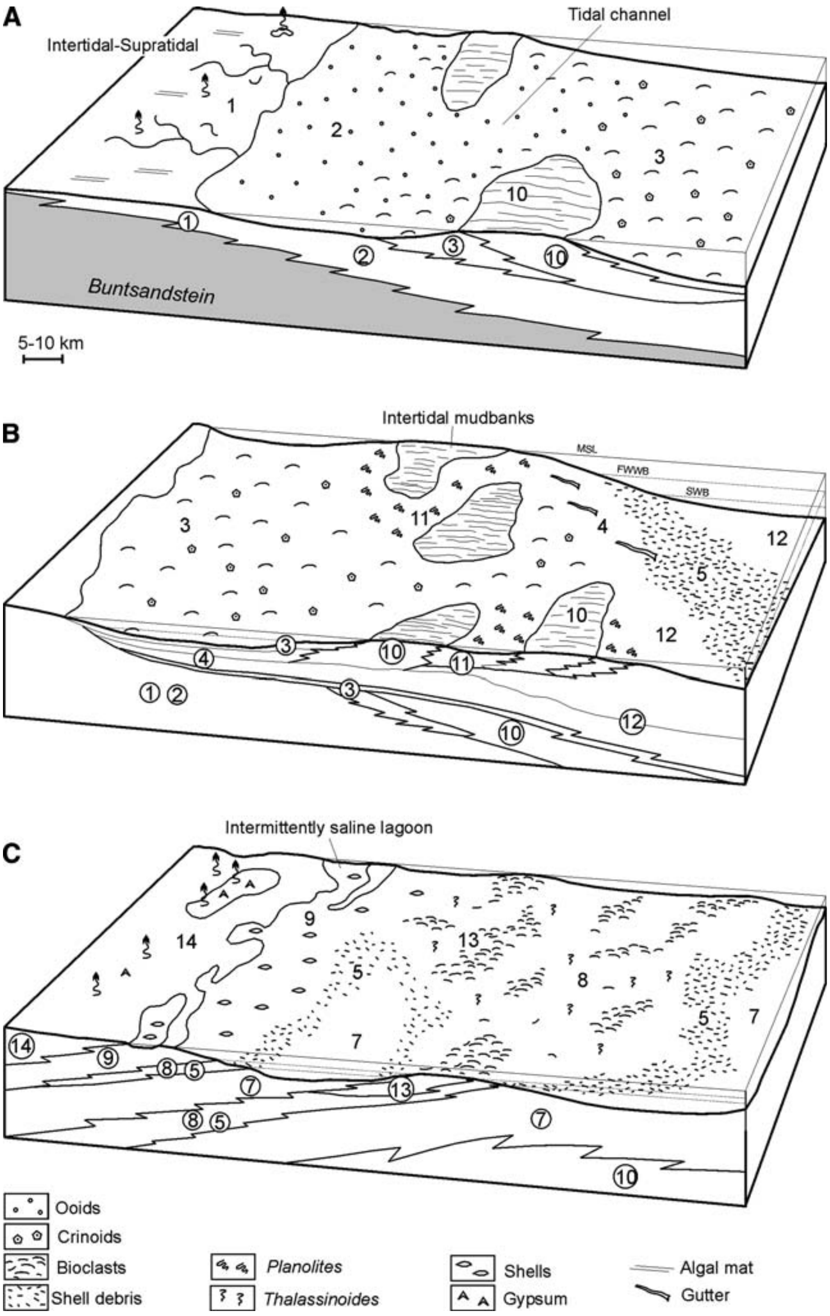

Fig. 20 Sedimentary model for the Muschelkalk carbonates in an epicontinental platform context indicating three stages. **a** Transgressive stage in which oolitic and bioclastic sediments were deposited over siliciclastic sediments (Buntsandstein facies). **b** Marine sediments were established. In the middle of the platform, the peritidal flat developed over some mudbanks. In this stage, the margin of the platform has a ramp profile: the lower member of Cehegín Formation is characterized by the slumps and gutter casts. **c** In the last stage, a prograding pattern developed. Coastal and lagoonal environments prograded over the deeper water sediments. This platform was characterized by low energy and the development of small shoals. Tempestite facies are more typical in the last stage owing to the flatter profile of the platform. In this stage, the sediments of the upper member were deposited

locally. In the Betic basin, the lagoon may have been partly barred by these mudbanks. These sediments of the lower member are, therefore, interpreted as ramp deposits of an epicontinental platform, in which only in some stages, a disrupted barrier-tidal complex developed with lagoons and tidal flats behind.

The lithofacies of the upper member of the Cehegín Fm are represented by thinner beds and a more repetitive pattern than the lower member lithofacies. In the Siles Fm, this is not clear because of the reduced thickness and less facies variation in the upper member. The lower part of this member is locally comprised of marly sediments. An abundance of marlstone, as in Facies 7, is characteristic of distal facies of an outer ramp, below the storm-wave base (Aigner 1985; Duringer and Vecsei 1998), although in Facies 7 some tempestites (Facies 5) occur. At the uppermost levels, shallower and, at the same time, relatively low-energy facies are typical (Facies 8). Thus, the deeper water sediments, or first sediments of Facies 7, pass up into lagoonal deposits of Facies 8, with abundant shells, algae and burrows. In some sections of the Cehegín Fm, nevertheless, many small coarsening-upwards cycles occur (Facies 7-8-13), which are interpreted as shallowing-upward cycles. It is possible that Facies 13 locally corresponds to small shoals that partly restricted a lagoon (Fig. 20c), but with connections to the open sea, since ammonoids appear even in the uppermost portion of the Cehegín Fm.

It should be noted that high-energy sediments correspond to: (a) the oolitic sediments of the lower member, related to tidal channels or coastal long-shaped bars or shoals; (b) the bioclastic limestone of the upper member, forming small shoals; (c) storm deposits present in both members. In no case were sediments that could be interpreted as deposits of large bars defining a lagoon observed. Offshore low-energy sediments pass to coastal muddy sediments with no intervening subaqueous or subaerial barrier. In the case of the lower member of the Cehegín Fm, it is likely that sites were restricted by the mudbank complex yet connected to the open sea. The upper member had lagoonal conditions owing to the presence of some shoals but also with connections to the open sea. This situation suggests low-wave energy, in that tidal flats developed although tides were of low range. Storms affected the sea floor since it was not very deep, although the tempestite record varies in the different sections. In general, this low-wave energy, occasionally stormy, environment was controlled by a complex of small broken shoals or banks on a huge platform of the shallow epicontinental sea. In this interpretation, it is interesting consider that these same facies developed throughout the Betic basin especially at the end of the Ladinian (López-Garrido et al. 1997; Pérez-López and Pérez-Valera 2007), not only in the areas where the Siles and Cehegín formations are defined. This indicates the spread of lagoon-type environments that were connected to the deeper-water areas where ammonoids developed or fine grain deposits occurred. This idea is consistent only with an epicontinental platform.

Sequence stratigraphy

In the model proposed for the Muschelkalk facies of the Southiberian Triassic, the carbonates of the Siles and Cehegín Fms are assigned to a third-order depositional sequence, which also includes the basal Buntsandstein facies within the Arroyo Molinos Fm (Pérez-Valera 2005). A lowstand—transgressive—highstand systems tract succession is proposed for this third-order depositional sequence (Fig. 17). The lowstand systems tract is represented by the Buntsandstein siliciclastic rocks of the Arroyo Molinos Fm. At the top of this formation, a transgressive surface can be recognised below the brown dolomites. Over this transgressive surface, one deepening-upwards and two shallowing-upwards cycles appear in the lower member of the Siles and Cehegín Fms. These cycles are better defined in the Cehegín Fm because they are marked by Facies 10, which stands out in the relief (Fig. 18e). The thickness of these cycles is 10–25 m. In the Cehegín Fm, the lower member shows a retrogradational pattern, manifested by thinning-upward successions of laminated limestone (Facies 10) in the three carbonate banks of thicknesses 20, 12 and 3 m, respectively (Fig. 17), which lie on top of the cycles. Our interpretation of this is an overall deepening-upward succession, developed during a transgressive systems tract (TST). At the top of the TST, the maximum flooding surface (mfs) was identified by Pérez-López et al. (2005) as a bioclastic bed rich in Involutinidae. This bed marks the input of Alpine faunas at the Ladinian transgression maximum, followed by beds with cephalopods (Facies 7), especially in Calasparra section (Fig. 12).

The upper member is composed of several shallowing-upwards cycles due to the progradation of the coastal-lagoonal system, over the offshore transition zone carbonates of the platform itself. These sequences are better represented in the Cehegín than in the Siles Fm, and span the Facies 7, 8 and 13, from marly deposits rich in cephalopods (Facies 7) to bioclastic limestones with *Thalassinoides* (Facies 13), representing the shallowing-upwards cycles. These cycles are not well represented in all the studied sections. The best section in which to see these cycles is the Cabra Sto. Cristo (Fig. 14), where there are four cycles of 5–11 m, with some thickening-upward patterns.

The presence in the upper member of cargneules and gypsum beds, along with marls and green lutites (Facies 14) indicates a general regressive tendency and a gradual change towards the Keuper facies. The sedimentary features of the upper member indicate an overall shallowing-upward succession with a progradation pattern, characteristic of a highstand systems tract (HST) (Fig. 17).

Lithostratigrafic correlations with other Triassic basins

The Triassic epicontinental shallow marine sediments of the Iberian Peninsula form part of the westernmost area of the Neotethys margin. Subsequent westward expansion associated to the Neotethys led to successive marine transgression-regression cycles along the eastern and southern margins of the Iberian Plate (López-Gómez et al. 2002). Carbonate deposits reached different interconnected basins, although with varying thicknesses and at different times.

In some Triassic basins of the Iberian Peninsula, it is possible to distinguish two carbonate units, dated as Anisian and Ladinian respectively, with a mudstone-evaporite unit between them (Fig. 21). For example, the Middle Triassic succession in the central area of the Iberian Ranges (Castilian branch) and in the Catalan Coastal Ranges, is represented by the two carbonate units separated by the mudstone-evaporite unit (e.g. López-Gómez et al. 1998, 2002). However, in regions such as the NW of the Iberian

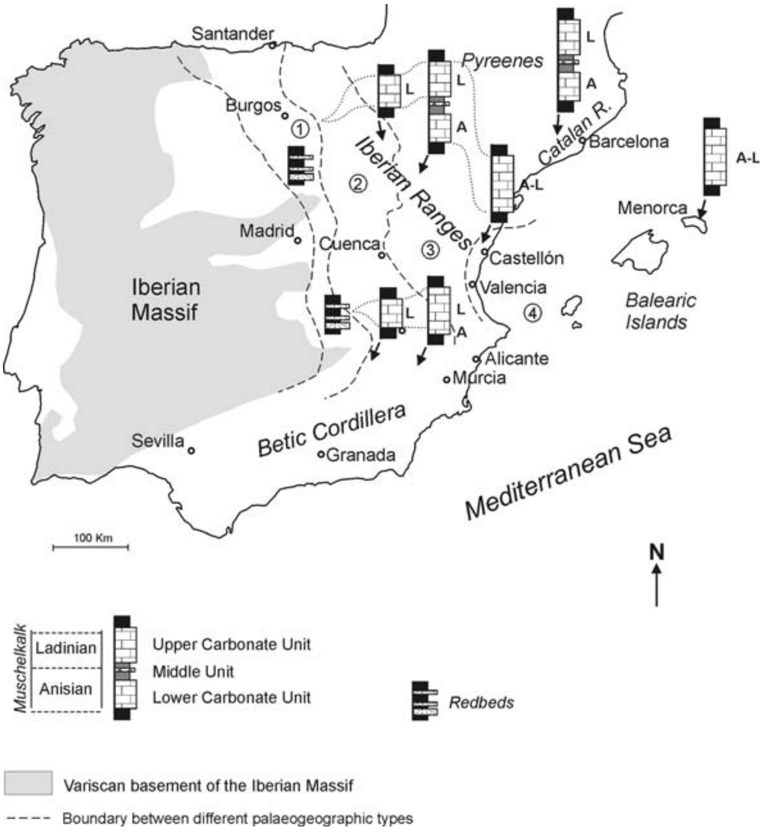

Fig. 21 Map of the Iberian Peninsula and Balearic Islands indicating the different stratigraphy of the carbonate units of the Muschelkalk. According to the Mushelkalk's stratigraphy, four palaeogeographic Triassic types can be distinguished (López-Gómez et al., 1998): *1* Hesperian Triassic (without Muschelkalk facies); *2* Iberian Triassic; *3* Mediterranean Triassic; *4* Levantine-Balearic Triassic. *A* Anisian; *L* Ladinian

Ranges (Aragonese branch), it is solely represented by the upper carbonate unit, because deposits of this age onlapped the western margin of the Palaeozoic Iberian Massif.

The Middle Triassic successions are also represented by a single carbonate unit towards to East, because the intermediate mudstone-evaporite unit gave way eastwards to carbonates (López-Gómez et al. 2002), as occurs in the Castellón province or in Menorca (Balearic Islands), where the carbonate unit is Late Anisian to Ladinian in age. This presence or absence of these carbonate units have been used as criteria for subdividing the Triassic palaeogeographic domains of the Iberian Peninsula (Fig. 21) (Virgili et al. 1977; Sopeña et al. 1983; Virgili et al. 1983; López-Gómez et al. 1998).

The Cehegín Fm consists of a single carbonate succession of Upper Anisian-Ladinian age, which is correlated with the Siles Fm, corresponding to the upper carbonate unit, or the Upper Muschelkalk, of the Iberian Peninsula. These formations are the same carbonate unit that extended towards the Iberian Massif (Figs. 1, 4a′). Therefore, the Siles and Cehegín formations are correlated with the carbonate unit of Ladinian age that belongs to the "Iberian Triassic" (Fig. 21). Obviously, the boundaries of these carbonate units, at least the lower ones, are not isochronous.

The Cehegín Fm is also correlated to the upper carbonate unit of the Catalan Coastal Ranges, although it displays more different facies. Moreover, the depositional sequences of the Siles and Cehegín formations, along with the siliciclastic lower unit (Arroyo Molinos Fm), are comparable to Depositional Sequence 2 defined by Calvet et al. (1990) for the Middle and Upper Muschelkalk in the Catalan basin, which is composed of depositional systems tracts: LST, TST and HST. The lower carbonate unit (Anisian) has not been defined in the External Zones of the Betic Cordillera, although it could be that it was not known until now, since there are some Triassic dolomite outcrops that have not yet been assigned to any unit.

The Siles and Cehegín formations can also be correlated with the Upper Muschelkalk of Germanic basin (Hauptmuschelkalk) due to their Late Anisian-Ladinian age. In addition, the depositional systems tracts of the Siles and Cehegín formations (TST and HST) are equivalent to the systems tracts defined for the Upper Muschelkalk in the Germanic basin (Aigner and Bachmann 1998).

Conclusions

The present study of the carbonate outcrops of the Muschelkalk facies in the External Zones of the Betic Cordillera provides a general stratigraphy for these sediments despite significant lithofacies variation from southern to northern areas. Two lithostratigraphic formations and 14 main facies types are differentiated and the lithostratigraphic variations of the Muschelkalk carbonates, from the Prebetic domain to the Subbetic domain, are characterized, although each formation does not necessarily match one domain.

The Cehegín Fm comprises sediments deposited during the Ladinian in the intermediate-external area of the South Iberian Palaeomargin. The formation is characterized by a succession of dark limestones, with dolomites at the base that pass to marly limestones and marls in the upper part. There is a notable presence of two or three laminated limestone beds in the lower member, and bioclastic limestone beds commonly appear in the upper one. Throughout the succession, typical beds with bioturbation structures (*Thalassinoides, Chondrites, Planolites*) occur. Pot and gutter casts are characteristic of the lower member, and tempestites of the upper one. In the studied successions, the most energetic levels corresponded to storm deposits.

The Siles Fm is defined as characterizing the Muschelkalk facies carbonates that correspond to Ladinian sediments in the most proximal areas of the South Iberian Palaeomargin. The Siles Fm consists of a single unit of carbonates, which in the Hornos-Siles sector, is repeated through tectonic effects. Two members can be distinguished: the lower one is characterized by the occurrence of paper-thin bedded marly limestones, and the upper one is made up of thin-bedded nodular limestones and some marly bed intercalations. In addition, the lower member features the presence of gutter casts, and the upper member exhibits abundant bivalves, mainly *Enantiostreon*.

Sedimentary interpretations for these formations suggest that these facies correspond to an epicontinental platform with a gentle slope at the margin, such as a ramp, that changed over time. Until the uppermost portions of the Muschelkalk successions, cephalopods appear in beds of both members. This margin of the platform was more or less restricted depending on the stage, but it always had a low-energy range.

In the lower member, a mudbank system developed in a ramp, corresponding to the laminated limestone of the Cehegín Fm. In the upper member, very small shoals of a relatively restricted lagoon prograded over offshore transition zone deposits. The first of these situations is related to a transgressive stage and the second to a progradational pattern in a highstand stage. Storms were important in this epicontinental platform, because the sea floor was normally above storm wave base although effects differ depending on the area. Tempestites are very common in some sections and appear less frequently in others. There is no evidence for a barrier to define a restricted lagoon; muddy sediments grade from deep-water to intertidal environments. The model presented is based on our main interpretation, that these sediments were deposited in a marginal zone of a large, shallow epicontinental sea, with a changing complex palaeogeography, which modified the wave energy, currents and effects of storms.

Both formations, Siles and Cehegín, consist of one carbonate unit of Muschelkalk facies, which can be correlated with the Upper Muschelkalk of different regions (e.g. Catalan Coastal Ranges, northern area of the Iberian Ranges or Germanic basin).

Acknowledgments The authors wish to thank Dr. José López Gómez, Dr. Ana Márquez Aliaga, Dr. Leopoldo Márquez, Dr. Alfredo Arche and Dr. Antonio Goy for their comments and great help with this study. We also thank M. Tucker for his constructive and thoughtful comments on the manuscript, Juan Alberto Pérez Valera and Pablo Plasencia for providing the ammonoid and conodont data and Ana Burton for revising the English. This work was funded by an "Ayuda Puente" from the University of Granada awarded to one of the authors (FPV), the Research Projects BTE 2002-00775, CGL2005-01520/BTE and the Grupo de Investigación de la Junta de Andalucía RNM 0163, along with Projects IGCP 458 and 467.

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