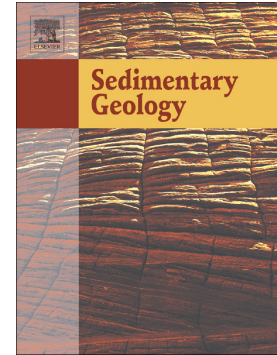


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Paleocene-Lower Eocene carbonate platforms of westernmost Tethys

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ABSTRACT

The Paleocene-lower Eocene succession is well exposed in Sierra Espuña-Mula Basin (Betic Cordillera, S Spain) and carbonate platforms are well represented as part of this succession. The study of the paleoenvironmental evolution of these platforms has allowed to cover an important gap in the knowledge in the westernmost Tethys. Thirteen microfacies (*Mf1* to *MF13*) were recognized based mainly on the fossil assemblage (principally larger benthic foraminifera), texture and fabric of the microfacies. The fossiliferous assemblage of the entire succession shows a mixture of photozoan and heterotrophic biogenic elements, typical of an inner to outer ramp environment of a warm temperate biogeographic province. Fragments of hermatypic corals

have also been detected in the lower part of the succession (Paleocene) allowing to think in propitious conditions in this period. The succession evolves upwards (Lower Eocene) to low-energy shallow marine protected environments (lagoon) in inner ramp settings. In addition, abundant porcelaneous larger benthic foraminifera such as alveolinids and soritids are indicative of euphotic shallow marine conditions in moderately oligotrophic upper subtidal environments. In the upper part of the succession, hermatypic corals as displaced fragments and in situ isolated coral phaceloid colonies also appear together with other biogenic components indicating warm shallow and euphotic marine conditions (coral-maërl environment). Lenticular larger benthic foraminifera, characterizing marine mesophotic and oligotrophic habitats can be found in the upper part of the middle ramp, and flattened larger benthic foraminifera forms indicating lowermost mesophotic conditions in a distal middle ramp. The obtained results have been compared with other similar Tethyan sectors obtaining a broader view. The biogenic marine association is characterized by the absence of the 'Lockhartia community' of the Tethyan domain, together with the dominance of alveolinids, nummulitids and orthophragminids. During most of the Paleocene, northern Mediterranean Tethys platforms were located in the middle paleolatitudes and characterized by coral-reef and coralgall biofacies. The studied platforms (located at a latitude close to 25°N) show, in a ramp-like context, underdeveloped in situ coral constructions probably of patch-reef type. In the early Eocene the expansion and abundance of the larger benthic foraminifera and the practical disappearance of coral took place in the sedimentary platform through the entire Tethys. However, in the study area small reef coral build-ups have also been observed in the lower Cuisian beds, indicating that in westernmost Tethys coral construction continued at these latitudes.

Keywords: Paleocene-early Eocene, Carbonate platforms, Westernmost Tethys, Larger benthic foraminifera, Paleoenvironmental evolution.

1. Introduction

During the early Paleogene rising temperatures (Thomas and Zachos, 2000; Zachos et al., 2001; Bernaola et al., 2007; Gilmour et al., 2014; Storme et al., 2014) led to the progressive decline of reef-building corals in the Tethyan domain while larger benthic foraminifera, which can tolerate higher temperatures, progressively became the main carbonate producer in platform environments (Kennett and Stott, 1991; Hottinger, 1998; Orue-Etxebarria et al., 2001; Pujalte et al., 2003; Scheibner et al., 2005; Scheibner and Speijer, 2008). Initially, corals were dominant while larger foraminifera were of minor importance. Later, corals were only present at middle latitudes and were replaced by larger benthic foraminifera at low latitudes. At the end of the early Paleogene the increase in temperatures in the oceans and CO₂ in the atmosphere led to the decline of corals and the expansion of larger benthic foraminifera (Scheibner and Speijer, 2008). During this period most of circum-Tethyan sectors became shallow marine, developing carbonate platforms and mixed carbonate-siliciclastic successions. In detail, the Tethyan carbonate platforms were mainly located in two rims: the northern border of this ocean at middle latitudes above 30° N; and the southern border at intermediate and low latitudes, mostly below 25° N (Baceta et al., 2004, 2005; Robador, 2005; Scheibner and Speijer, 2008; Pomar et al., 2017). The northern border platforms can mainly be found nowadays in the Pyrenees, Greek peninsula and islands, Slovakia, the Alps, the Apennines (Italy), the Adriatic platform and Turkey; while the southern border platforms presently crop out in the northern Atlas (N Morocco), N Tunisia, Libya, Egypt, NW Somalia, Oman, Tibet and N India.

According to paleogeographic models (Guerrera et al., 2005, 2019; Guerrera and Martín-Martín, 2014; Martín-Martín et al., 2006; Martín-Martín et al., 2020a,b), the Betic-Rif Cordillera (S Spain and N Morocco) occupied an intermediate position to the former two rings at middle

latitudes (between 25°-30°). In the Betic branch of this cordillera, early Paleogene carbonate platforms are common in the internal (Malaguide) at about 25° N and external (Prebetic) units at about 30° N; while in the Rif (Morocco) this kind of deposits can be found in the internal (Ghomaride) units also at about 25° N. In both cases, these fossil platforms represented the transition at middle latitudes to the proto-Atlantic domain, but they are still not well studied.

Taking into account westernmost post-Cretaceous Tethyan paleogeography, the western Mediterranean area was characterized by two oceanic branches separated by a microcontinent (Martín-Martín et al., 2020a,b). The northern branch consists of the Prebetic and Subbetic units of the External Betic Cordillera, while the southern one is represented by the Maghrebian Flysch Basin, itself connected with a sector of the proto-Atlantic Ocean, still in extension and currently corresponding to the Malaguide and Ghomaride units from the internal Betic and Rif Cordillera (Guerrera and Martín-Martín, 2014; Guerrera et al., 2019; Martín-Martín et al., 2020a,b).

The present study proposes the reconstruction of the main evolutionary stages and related paleoenvironmental features of some Paleocene-lower Eocene carbonate platforms analyzed in the Internal Betic Cordillera and is especially focused on the coeval successions of the Malaguide (internal) units (Sierra Espuña, Murcia province). The study of this area tries to cover the gap in knowledge at middle latitudes between the southern and northern rims of platforms in the Tethys, but also, in the westernmost part of the above-mentioned ocean, in the transition to the Atlantic domain. The analysis also takes into consideration the larger benthic foraminifera (LBF) symbiont-bearing organisms that require specific environmental conditions, providing specific information on the amount of available light, temperature, and presence of nutrients in the marine environment. Thus, study of the evolution of the LBF in the successions, as well as changes in fossiliferous assemblages, can be used as indicators of environmental changes. The so-called “Global Community Maturation Cycles” (GCMC) (Hottinger, 2001), is useful to divide the stratigraphic record into biochronostratigraphic units characterized by intervals of gradual

evolution of the LBF, that are delimited by abrupt taxonomic events of change both in abundance and diversity of these assemblages. Such a division, closely associated with LBF biozones, can be used to extract additional sedimentary, paleoenvironmental and paleoclimatic information, facilitating comparison between different Tethyan sectors.

A specific topic concerns the description and interpretation of the plentiful Paleocene-lower Eocene micro- and macrofacies outcropping in Sierra Espuña and its neighbouring areas. The biostratigraphic analyses used in this study are based on benthic communities living in shallow marine waters and especially on larger benthic foraminifera. These associations also allow for biostratigraphic correlation with the biozonations of Serra-Kiel et al. (1998b).

The selected study area (Fig. 1A) shows one of the most complete and well exposed Paleogene shallow marine successions recognizable in the Internal Betic-Rif Chain (usually metamorphosed and affected by deformation), providing information at middle palaeolatitudes at about of 25° N.

2. Geological Setting

2.1. *The Paleocene-early Eocene in Betic Cordillera*

The study area is located in the Sierra Espuña-Mula Basin (SE Spain, Betic Cordillera; Fig. 1A). The formations analyzed in detail (Mula, Espuña and Valdelaparra Fms) belong to the Internal Betic Zone (Fig. 1D).

The Betic Cordillera constitutes the westernmost branch of the Eo-alpine and Neo-alpine peri-Mediterranean chains (Fig. 1B). The tectono-sedimentary evolution of these chains was controlled by the presence of one or more microplates between Iberia-Eurasia and Africa Plates

surrounded by two Tethyan oceanic branches (Guerrera et al., 2005, 2019; Guerrera and Martín-Martín, 2014; Perri et al., 2013, 2017; Martín-Martín et al., 2020a,b) (Fig. 1C).

The northern oceanic branch consists of the Prebetic and Subbetic units of the External Betic Cordillera, while the southern one is represented by the Maghrebian Flysch Basin, currently corresponding to the Malaguide and Ghomaride units from the Internal Betic-Rif Cordillera. The lower Paleogene platform recorded in the Betic domain is restricted to the Prebetic domain (from Jaen to Alicante provinces, S and SE Spain) to the north and to the Malaguide domain (from Malaga to Murcia provinces, S and SE Spain) to the south. The stratigraphic record of the Prebetic platform during the Paleocene was divided into two stratigraphic unit separated by an unconformable boundary marking an abrupt change in sedimentation with a deepening of the depositional area (Chacón and Martín-Chivelet, 1999, 2005; Martín-Chivelet and Chacón, 2007; Guerrera et al., 2014). The lower unit consists of several marine shallowing upward sequences that evolve from outer to inner platform depositional settings. The upper unit consists of a middle-outer ramp or the transition to a marine slope environment. The early Eocene platforms are characterized by carbonate litho-biofacies arranged into six shallowing upward sedimentary cycles evolving from middle ramp settings, with abundant nummulitids and orthophragminids, to inner ramp ones with alveolinids. In some eastern sectors, coralline red algae and echinoids are also noted (Geel, 2000; Vera, 2000; Chacón and Martín-Chivelet, 2005; Guerrera et al., 2006, 2014; Höntzsch et al., 2013).

The Cenozoic succession in the Sierra Espuña-Mula Basin belongs to the Morrón de Totana Unit (Malaguide Complex, Internal Betic Zone) that comprises several formations (Fig. 1D) arranged into pre-orogenic (Paleocene-lower Oligocene), syn-orogenic (upper Oligocene-Burdigalian) and late- to post-orogenic (middle-upper Miocene) tectono-sedimentary cycles (Martín-Martín, 1996; Martín-Martín et al., 1997a, 1997b, 1998; Serra-Kiel et al., 1998a; Perri et al., 2017; Martín-Martín and Robles-Marín, 2020).

The Morrón de Totana Unit (Fig. 1E) is tectonically differently arranged, being involved in an antiformal stack in the Sierra Espuña Basin and affected by thrust sheets in the Mula Basin. More generally the study sector corresponds to the Internal-External Zone Boundary of the Betic Cordillera.

As concerns the sedimentary formations belonging to the Morrón de Totana Unit, the stratigraphic record reported in Figure 2 shows several units lying above the Cretaceous substratum (Capas Blancas Fm), their lateral and vertical relationships, and an Ilerdian gap between the Mula and Espuña fms.

2.2. Stratigraphy of the Paleocene-early Eocene in the study area

Locally it is difficult to establish the boundaries between different Paleocene chronostratigraphic units. The low diversity in fossil assemblages, together with the absence of bio-markers caused by lateral variation of sediments, make it difficult to establish a precise biostratigraphic identification of these units. Moreover, some intra-Paleocene discontinuities are also detected. The GSSP (Global Boundary Stratotype Section and Point) of the Selandian Age (Danian/Selandian boundary) in the Zumaia area (Basque Country, Spain) is gradual, without biostratigraphic discontinuity, and identifiable only by lithological and coloration changes (Schmitz et al., 2011).

Stratigraphic studies were carried out in the Mula, Espuña and Valdelaparra fms that provided detailed biostratigraphic data (Fig. 2) including LBF, planktonic foraminifera and calcareous nannoplankton, and can be compared with previous analyses. The Paleocene Mula Fm representing an inner to external platform depositional system is only represented in the Mula Basin area consisting of three intervals (Martín-Martín et al., 1998): (a) alternations of marls and silts with calcarenite and arenite layers (60 m thick), (b) massive biocalcarenites to arenites with

stratified and thick algal beds mainly with cross lamination (5 m thick), and (c) poorly stratified calcarenites, biocalcarenes and arenites with algae and miliolids (40 m thick). The early Eocene represented in the entire study area consists of two laterally related stratigraphic formations (Martín-Martín et al., 1997a, 1997b): (a) the Espuña Fm outcropping in the entire study area represents an inner to external platform depositional system and consists of limestones and calcarenites with very frequent large alveolinids, nummulitids and algae, with a variable thickness (18 to 55 m); and (b) the Valdelaparra Fm is exposed only in the Sierra Espuña area representing a lagoonal depositional system and made of an ensemble of variable thickness (25 to 73 m) made of micritic limestones with miliolids, occasional alveolinids and *Orbitolites*, and mudstones with occasional beds of freshwater gastropods rich limestones. The general morphology and distribution of the depositional systems and stratigraphic formations of the Mula Basin-Sierra Espuña areas are summarized in Figure 2.

In this area the boundaries between Paleocene formations are marked by lithological changes similar to that established for the base of the Selandian unit in Denmark where the boundary was originally described (Schmitz et al., 2011; and references therein). Serra-Kiel et al. (1998a) recognized that the Selandian deposits in Sierra Espuña can be recognized by the common presence of species *Miscellanea globularis*, assigned to biozone SBZ 2 zone. Later, Hottinger (2009) reassigned this species to the genera *Miscellanites* and included it in the latest SBZ 2 and SBZ 3 zones of Serra-Kiel et al. (1998b). The Selandian/Thanetian boundary, not recognizable in the field, could coincide with the later occurrence of Selandian deposits in the Doñana stratigraphic section. Instead the upper Paleocene deposits show distinct lithofacies with respect to the previous stratigraphic interval, without characteristic LBF key markers but supported by planktonic foraminifera dating as observed in the Castillo de Mula stratigraphic succession.

3. Methods and materials

The methodological approach in this study consists of field geological reconstruction of the Paleocene-early Eocene stratigraphic record, lithological features, sedimentological observations, and laboratory analyses mainly addressed to define the fossiliferous content, especially for the large foraminiferal content, which is very abundant at different stratigraphic levels.

The tectonic structures and their relationships are shown in Figure 1E. Four stratigraphic sections (Doñana, Castillo de Mula, Malvariche and Prado Mayor) have been studied in detail, measuring (bed by bed) the succession for a total of 290 m thickness, and also sampled in detail for laboratory analyses. The main lithofacies characteristics of the Paleocene-lower Eocene successions have been reconstructed summarized in Table 1 and Figures 1 and 3. Two logs were measured in the Mula Basin (Doñana and Castillo de Mula) and another two in the Sierra Espuña area (Prado Mayor and Malvariche). Ten samples (1-10) were collected in the Doñana section, ten (11-20) in the Castillo de Mula section, eleven (38-48) in the Prado Mayor section, and seventeen (21-37) in the Malvariche section.

During fieldwork, different litho-biofacies were differentiated and described (Table 1). The main changes in the composition of LFB were characterized in the field with the lens allowing selective sampling when microfacies changed. A total of 48 samples were utilized for the microfacies analysis. Standard thin sections (2.0 x 3.0 cm) were prepared and studied in order to interpret paleoecological features and depositional paleoenvironments using an optical microscope Nikon Eclipse E 200. A variable amount (from 3 to 8) of thin sections was performed for each sample depending on the size of the LFB (larger number of thin sections when LFB were of great size). Photographs were taken with a digital camera Nikon DS-Fi2 and

images were transferred to a PC computer using a Nikon's Digital Sight DS-U3 microscope camera controller and treated with the microscope imaging software Nikon NIS Elements F4.

Microfacies analysis includes the description of lithology, grain type (skeletal/non skeletal), size and sorting, textures and microfossil assemblages according to Flügel's (2010) methodology. For the denomination of microfacies, we used the terminology according to Embry and Klovan (1971), an extension of Dunham's (1962) classification of carbonate rocks. In order to differentiate microfacies assemblages, all the allochem components and matrix were characterized and visually estimated from the thin sections. The results were plotted according to the relative abundance of each component, with the terms present (if the element appears at least once in the thin section), common (when the element appears at least once in the area delimited by the objective x4 of the optical microscope) and abundant (when the element appears 2 to 4 times in the above defined area).

The taxonomic classification used for nummulitids is based on Loeblich and Tappan (1987). The genus *Assilina* includes both traditional evolute tests with low spiral growth forms (*Assilina* s.s.) and the evolute open spiral growth forms with simple septa (not folded) corresponding to the genus *Operculina* 'à septes simples, non plissés' of Hottinger (1977), here named 'operculiniform *Assilina*'.

Ramp-like platforms were interpreted since the studied facies resulted quite homogeneous during the early Eocene in the entire study area (from Sierra Espuña to Mula Basin) with a great extension (about 25 km in dip and about 15 km in strike). Marine palaeoenvironment reconstruction is carried out using the ramp subdivision terminology according to Burchette and Wright (1992) and Pomar (2001b) but considering also the photic subdivisions according to Pomar et al. (2017) such that the 'mesophotic zone' appears. The absence of true coral reef structures and, contrarily, the great development of larger foraminifera dominated belts, more in line with a ramp model, better fit with these models.

In particular, we consider allowing the terminology of Pomar's work, that the uppermost boundary of this mesophotic zone could coincide with the lower limit of occurrence of marine vegetation, corresponding approximatively to the fair weather wave base (fwwb), and the lowermost boundary with the storm wave base (swb) that, although problematic to interpret, we consider it to be in the transition point where in situ hyaline larger foraminifera assemblages dominate over porcelaneous ones. The upper boundary also coincides with the chlorocline sensu Liebau (1984) in Pomar et al. (2017), which is the lower limit of modern seagrass and in situ green algae. For the lower limit of the mesophotic zone, these authors only specify that it is commonly located below the normal wave base. Lastly, morphologic terminology used to describe the growth of crustose coralline red algae is based on Nebelsick and Bassi (2000).

The obtained results are discussed and compared with coeval successions of the Pyrenees and Betic Cordillera realms. In addition, similarities and differences with other sectors of Central Tethys are also discussed.

4. Results

4.1. Litho- and biostratigraphy

In the measured and analyzed Doñana stratigraphic section (Mula Basin, Log. 1, thickness 95 m), two main lithostratigraphic intervals have been recognized in the Mula Fm (Fig. 3). The lower one (**P1**, thickness 60 m) is constituted by alternating marls and silts with calcarenite and arenite layers. The succession is poorly stratified and usually no sedimentary structures are observed. The lower 30 m of the interval represents a parasequence showing an increase in number and thickness of fine to coarse grained, laminated in the upper part, calcarenite beds. In the lithofacies fragments of gastropods are common. The upper interval (**P2**, thickness 5 m) is

constituted by massive biocalcarenites to arenites with stratified and thick algal beds mainly with cross lamination (0.5 cm thick laminae). Up to mm-scale calcareous clasts (medium to coarse sand) occasionally occur. In this massive interval, only the basal bed (thickness 1 m) is stratified.

In the stratigraphic section of the Castillo de Mula (Mula Basin, Log 2, thickness 54 m) a lower interval (**P3**, 40 m thick, Mula Fm) is characterized by poorly stratified fine to medium grain size calcarenites, biocalcarenites and arenites with algae and miliolids from the Paleocene (Martín-Martín et al., 1998). Occasional interlayers of silt-sandy marls appear. Bed thickness changes laterally and vertically between 10-20 cm and 1 m. An erosion surface corresponding to a stratigraphic gap (Ilerdian *p.p.*: everywhere missing) marks the bottom of the lower interval (**F1**, 4 m thick) of the Espuña Fm (Cuisian-early Lutetian: Martín-Martín et al., 1997a,b), separating the latter from the underlying Mula Fm. The interval F1 shows poorly stratified and amalgamated biocalcarenites (fine to medium grained) with sometimes up to some cm-scale algae (rodholites) and *Nummulites*. The upper interval (**F2**, thickness 10 m) consists of massive amalgamated medium to coarse grain biocalcarenite beds, laterally varying in thickness and with a lens-shaped structure.

This stratigraphic section (Fig. 3: Sierra Espuña, Log 3, thickness > 121 m) extends from the upper part of the Capas Blancas Fm (> 30 m thick), the Mula Fm (with a thickness of 2 m), and the Espuña Fm (in this section only 18 m thick) to the base of the Valdelaparra Fm (73 m thick). The boundary between the Capas Blancas Fm and Espuña Fm is marked by an erosive surface (stratigraphic gap) corresponding to the Paleocene early Eocene succession of the Mula Fm. Laterally, a small outcrop of Paleocene continental *Garumnian*-like facies can be found. It consists of continental reddish beds with articulated *Microcodium* in situ. It has not been possible to sample a level useful for thin section studies. Resting on another unconformity, the Espuña Fm (Cuisian *p.p.* in this stratigraphic section: Martín-Martín et al., 1997 a,b) is represented by four different lithofacies (**A1**, **A2**, **A3**, **A4**). The main characters of these lithofacies are as

follows: **A1**, limestones tens of m in thickness with microconglomerate bands (mm- to cm-scale quartzite clasts) and less frequent alveolinids; **A2**, m-scale biomicritic limestones with very abundant Alveolinae and less frequent *Nummuites*, *Assilina*, operculiniform *Assilina* and *Nummulites* (the latter less abundant than *Assilina*); **A3**, fine biocalcarenes with very abundant *Nummulites* and very rare alveolinids; **A4**, dm-thick micritic limestones characterized by poor fossil content; in the upper part up to 20-30 cm large frondescent corals are frequent. The Valdelaparra Fm (latest Cuisian p.p. in this stratigraphic section: Martín-Martín et al., 1997 a,b), which appears at the top of the succession, is represented by three different lithofacies (**G**, **H1**, **H3**). The main characters of these lithofacies are: **G**, amalgamated blackish-gray and brownish micritic limestones with abundant miliolids, occasional alveolinids and *Orbitolites*; **H1**, (partially covered): homogeneous yellowish-gray silty-sandy mudstones with occasional dm-scale beds of arenites (quartz, muscovite, lithic fragments, etc.) with a calcareous cement (pelites/arenites + limestones ratio = 95/5); **H3**, freshwater gastropod rich limestones (pelites/arenites+limestones ratio =70/30).

The stratigraphic section of Malvariche (Fig. 3: Sierra Espuña, Log. 4, thickness 100 m) extends from the upper part of the Cretaceous Capas Blancas Fm (> 20 m thick), to the Espuña Fm (55 m thick and Cuisian p.p. in this stratigraphic section: Martín-Martín et al., 1997 a,b) and to the lower part of the Valdelaparra Fm (25 m thick and latest Cuisian p.p. in this stratigraphic section: Martín-Martín et al., 1997 a,b). In the Espuña Fm six different lithofacies (**A**, **B**, **C**, **D**, **E**, **F**) have been recognized, which are partly repeated (Table 1). The main characters of these lithofacies are as follows: **A**, dm-scale fine limestones and calcarenites with cross bedding, and with very frequent large alveolinids with dimensions up to 1-2 cm, while *Nummulites* are missing; **B**, gray-yellowish marly-pelites; **C**, gray-blackish micritic limestones; **D**, biocalcarenes with rounded pebbles of quartz with occasional plane-parallel lamination and often characterized by a conglomeratic base (clasts up to 4-8 cm diameter) and very abundant

Nummulites, alveolinids and echinoderms (without algae), often concentrated in pockets or coarser levels (fine to coarse grain size); **E**, abundant alveolinids and less frequent *Nummulites*; pockets and bands very rich in fossils that are coarser than the matrix; sometimes with *Solenomeris* (encrusting benthic foraminifera); **F**, as litho-biofacies **E** but in this section it is characterized by stratified dm-scale beds of bio-calcarenites and by much more abundant *Nummulites* than alveolinids. The Valdelaparra Fm, appearing at the top of the succession, is represented by lithofacies **G**. It consists of amalgamated blackish-gray and brownish micritic limestones with abundant miliolids, occasional alveolinids and *Orbitolites*.

In summary, a regional unconformity marks the top of Cretaceous deposits to separate the Capas Blancas Fm (Sierra Espuña) from the Paleocene Mula Fm that crops out in the Mula Basin (very reduced and characterized by continental facies in Sierra Espuña). The Mula Fm is mainly characterized by marls and frequent calcarenites and arenites (Logs 1 and 2). Three members have been recognized in this formation: lower member (P1, Danian; SBZ 1-2: Martín-Martín et al., 1998); middle member (P2, Selandian; SBZ 3: Martín-Martín et al., 1998); and upper member (NP9 zone of Martini, 1971; P4-P5 zones of Berggren et al., 1995; P3, Thanetian: Martín-Martín et al. 1998). The lower and middle members have been defined in the Doñana stratigraphic section (Figs. 1-3); while the upper one was defined in the Castillo de Mula stratigraphic section, correlated with the LBF zones SBZ 3-4 of Serra-Kiel et al. (1998b). In the Doñana stratigraphic section (Log 1) lower Paleocene deposits indicating shallow marine sedimentation were recognized. Instead, the oldest deposits (upper Thanetian; SBZ 4: Martín-Martín et al., 1998) of the Castillo de Mula stratigraphic section (Log 2) indicate an open marine paleoenvironment marked by planktonic foraminifera. In the Prado Mayor stratigraphic section (Log 3), the Mula Fm is represented only in a lateral position, with a much-reduced thickness and characterized by continental *Garumian*-like facies (Martín-Martín et al., 1998), indicating the occurrence of emerged lands in the Sierra Espuña area during this period.

A second unconformity between the Mula and Espuña Fms represents a new discontinuity recognized in the study area which corresponds to a stratigraphic gap covering the entire early Ypresian (Ilerdian). The lower Eocene deposits (Cuisian, late Ypresian; SBZ10-12: Martín-Martín et al., 1997a,b) cropping out in the Mula Basin as a condensed succession are well developed in Sierra Espuña area. These deposits are represented by two lateral and coeval formations: the marine calcareous Espuña Fm and the marshy-continental marly Valdelaparra Fm.

The Espuña Fm has been defined in the Castillo de Mula, Malvariche and Prado Mayor stratigraphic sections (Logs 2-4, respectively; Figs. 1-3). Two members have been recognized in the formation: (i) the lower member (lower Cuisian; SBZ 10: Martín-Martín et al., 1997a,b), and the upper member (middle Cuisian; SBZ 11: Martín-Martín et al., 1997a,b). The upper portion of the Valdelaparra Fm is referable to the lower Lutetian (SBZ 13: Martín-Martín et al., 1997a,b), according to LFB assemblages; the SBZ 12 zone (upper Cuisian: Martín-Martín et al., 1997a,b) has not been recognized in this area with larger foraminifera. Limestones and sandy calcarenites characterize the lithofacies of the marine Espuña Fm while micritic limestones are present in the Valdelaparra Fm, related to a transition environment and with which the Espuña Fm interfingers laterally and vertically (Martín-Martín, 1996; Martín-Martín et al., 1997a,b).

4.2. *Microfacies description*

On the basis of the fossiliferous assemblage, texture and fabric, fourteen microfacies (*Mf1* to *Mf13*) have been recognized and named according to the first appearance in the analyzed stratigraphic sections (Table 2, Figs. 4-7). The microfacies identified are as follows: *Mf1* to *Mf4* in Section 1 (Doñana) (Table 2, Figs. 4, 5); *Mf5* to *Mf10* in Section 2 (Castillo de Mula) (Table

2; Figs. 4, 5); *Mf8*, *Mf9* and *Mf11* to *Mf13* in Section 3 (Prado Mayor) (Table 2; Figs. 4, 5); *Mf8*, *Mf9* and *Mf11* to *Mf13* in Section 4 (Malvariche) (Table 2, Figs. 6, 7). A detailed description of all microfacies is reported below, the terminology used to describe the relative abundance of each component (present, common and abundant) is explained in the Methodology section.

Mf1 - Quartzsiltite to quartzarenite with gastropods (Table 2, Figs. 4, 5). Outcropping in the stratigraphic section 1 (Doñana), it consists of dark-quartzsiltite to quartzarenite with abundant angular quartz grains (20%). Small gastropods (10%) are common as well as discorbids and other hyaline small benthic foraminifera (5%), ostracods (5%) and dasyclade algal remains (2-3%). Other foraminifera such as small rotaliids, textulariids and miliolids, rare planktonic foraminifera, and reworked remains of *Microcodium*, in corn-cob aggregates and disarticulated grains, are also present. This microfacies shows a thickness of almost 30 m corresponding to lithofacies P1 made of marls and calcarenites (Table 1, Fig. 3).

Mf2 - Rhodolith and coral floatstone-packstone (Table 2, Figs. 4, 5). This grayish microfacies, poorly to moderately sorted, includes coral pebbles (ϕ : 4-6 mm; 15-20%) encrusted by crustose coralline algae (15-20%) and a debris of non-geniculate and geniculate coralline algae (10-15%) into a packstone bioclastic matrix with abundant small miliolids (10%). The complex miliolid *Idalina* (5%), hyaline small benthic foraminifera (discorbids, bolivinids, rotaliids) (10%), lunulitiform and vinculariform colonies of bryozoans (10%), gastropods (5%), and echinoid plates and spines (5%) are common. Subangular to subrounded quartz grains and reworked *Microcodium* debris (2-3%) are frequent. Other bioclastic remains (7-10%) such as hyaline encrusting foraminifera *Solenomeris* and agglutinated haddonids, textulariids, dasyclads, codial *Ovulites*, ostracods and annelids also occur. This microfacies is present only in stratigraphic section 1 (Doñana) with a thickness of more than 30 m and also corresponds to lithofacies P1 made of marls and calcarenites (Table 1, Fig. 3).

Mf3 - Coral and red algae grainstone-packstone (Table 2, Figs. 4, 5). This microfacies, moderately sorted, includes abundant rounded pebbles and grains of coral (ϕ : 6 mm; 5%), *Solenomeris* (ϕ : 4-5 mm; 10%), warty to lumpy growth forms of crustose coralline algae (*Sporolithon*) (ϕ : 3 mm; 10%) and intraclasts (ϕ : 1 mm; 5%) in a grainstone to packstone matrix where foraminifera such as small miliolids (5%) and miscellanids (7%) constitute main components of the fabric. Complex miliolid *Idalina* (2-3%), hyaline small benthic foraminifera (discorbids and small rotaliids) (3%), abraded and rounded grains of geniculate coralline red algae (3%) and other biogenic elements such as bryozoans (3-5%) or echinoid plates and spines (3%) are common. Abraded and rounded larger foraminifera fragments of *Glomalveolina* and *Elphidium*, reworked neorotaliid grains with a conspicuous micritic envelope, and valvulinids, haddonids, dasyclads, fragments of molluscs (gastropods, pelecypods) and annelids are present too. This microfacies is only present in stratigraphic section 1 (Doñana) with a reduced thickness of about 3 m and corresponds to lithofacies P2 made of massive biocalcarenites with cross lamination (Table 1, Fig. 3).

Mf4 - Crustose coralline algae and *Solenomeris* bindstone (Table 2, Figs. 4, 5). In this microfacies, poorly to moderately sorted, abundant macroids of the acervulinid *Solenomeris* (ϕ : 4-5 mm; 15-20%) and pebbles of corals (ϕ : 3-5 mm; 10%) encrusted by warty to fruticose crustose coralline red algae (15-20%) can be observed. In the voids of these growth structures small miliolids (5-10%) are abundant. Intraclasts (ϕ : 1 mm; 5-10%), lithoclasts (ϕ : 1 mm; 2-3%), and a debris of crustose and geniculate coralline (5%), peysonelliacean red algae (*Polystrata alba*) (2-3%), codiacean green algae (3-5%), miscellanids (3-5%), membraniporiform and adeoniform colonies of bryozoans (5%), and echinoid plates and spines (5%) are common. Other biogenic components are small rotaliids (2-3%), textulariids (2%), encrusting agglutinates (haddonids) (2-3%), dasycladacean green algae (2%), bivalve remains (2-3%) and serpulid worm tubes (2%). This microfacies is present only in stratigraphic section 1 (Doñana) with a reduced

thickness of about 2 m and corresponds to lithofacies P2 made of massive biocalcarenes with cross lamination (Table 1, Fig. 3).

Mf5 - Coral and *Solenomeris* floatstone-packstone (Table 2, Figs. 4, 5). In this microfacies abundant coral (ϕ : 3-6 mm; 10%) and *Solenomeris* (ϕ : 2-3 mm; 30-40%) pebbles embedded in a packstone matrix constituted by a crustose and geniculate coralline debris (10-15%), a diverse foraminifera assemblage with discorbids, miliolids, miscellanids, textulariids and small rotaliids (10-15%), common lunulitiform and adeoniform colonies of bryozoans (5%), and echinoid plates and spines (5%) can be observed. Dasyclads, solenoporaceans (*Elianella elegans*), haddonids and fragments of undeterminate molluscs are present (5-10%). This microfacies is present only in stratigraphic section 2 (Castillo de Mula) with a thickness of more than 20 m and corresponds to lithofacies P3 made of stratified calcarenites, biocalcarenes and arenites (Table 1, Fig. 3).

Mf6 - Quartzarenitic wackestone with planktonic foraminifera (Table 2, Figs. 4, 5). This well sorted microfacies is composed of quartzsiltite to fine-grained quartzarenite with dispersed skeletal components represented by common discorbids (2-3%), small rotaliids (5%), textulariids (2%), planktonic foraminifera (5-10%), bryozoans (2%), echinoid plates (2%) and aggregate grains (2%). Some dasyclades and fragments of molluscs are present (2-3%). This microfacies is only present in stratigraphic section 2 (Castillo de Mula) with a thickness of more than 10 m and as the previous microfacies corresponds to lithofacies P3 made of stratified calcarenites, biocalcarenes and arenites (Table 1, Fig. 3).

Mf7 - Rhodolith, nummulitid and orthophragminid floatstone (Table 2, Figs. 4, 5). This microfacies, moderately to well sorted, shows abundant rhodoliths constituted by *Sporolithon* (ϕ : 3-4 mm) and other crustose coralline algae (15%), and *Solenomeris* macroids (ϕ : 3-6 mm; 15%), often both covered by other encrusting foraminifera (mainly acervulinids, and rare planorbulinids and haddonids) (15%), into a finer biocalcarenitic matrix composed by common remains of geniculate and crustose coralline algae (5%), rotaliids (5%), vinculariform bryozoans

(2%), echinoid plates and spines (5%), abundant pellets and bioclastic grains with micritic envelopes (5-10%). Abundant tests of hyaline LBF such as *Nummulites* (15%), *Discocyclusina* (8-10%) and *Asterocyclusina* (2%), wrapped by crustose coralline algae and/or encrusting foraminifera, constitute the inner core of rhodoliths and macroids, analogous to the *Nummulites*-Rhodolith facies described by Rasser (1994). Other LBF tests are also common, such as operculiniform *Assilina* and *Amphistegina*. The problematic red algae *Distichoplax biserialis*, *Sphaerogypsina*, ostracods, serpulid worm tubes, small benthic foraminifera (miliolids, textulariids, valvulinids, bolivinids) and planktonic foraminifera are other biogenic components. This microfacies is only present in stratigraphic section 2 (Castillo de Mula) with a reduced thickness of about 5 m and corresponds to lithofacies F1 made of amalgamated biocalcarenes with algae (Table 1, Fig. 3).

Mf8 - Coral, acervulinid macroid and rhodolith bindstone-floatstone (Table 2, Figs. 4, 5). This microfacies, poorly to moderately sorted, shows a mixed bindstone-floatstone texture with rhodoliths (*Sporolithon*) (ϕ : 4 mm; 10%), *Solenomeris* macroids (ϕ : 2-3 mm; 10-15%) wrapped by crustose coralline algae (*Lithoporella* and others) (10-15%) and encrusting foraminifera as planorbulinids, *Acervulina* and *Miniacina* (10-15%). There are common coral-bryozoan (ϕ : 5-7 mm; 5-10%) and intraclast pebbles (ϕ : 3 mm; 2-3%), embedded in a calcarenitic packstone bioclastic matrix constituted of abundant bryozoan colonies (5-10%), coralline algae *Distichoplax biserialis* (5%) and a common crustose coralline algal debris (2-3%), rotaliids (neorotaliids, victoriellids) (2-3%), small miliolids (2-3%), discorbids (2-3%), remains of molluscs (gastropods and pelecypods) (5%), echinoid plates and spines (5%) and abundant pellets (5-7%). Isolate specimens of *Alveolina* (5%), *Nummulites* (2-3%) textulariids (2-3%), fragments of dasyclade and codiacean green algae (5%) and rounded reworked grains of *Glomalveolina* and neorotaliids (2-3%) are also present. In the field this microfacies is included into lithobiofacies A 4a (Table 1) where the presence of in situ coral phacelloid colonies of

decimetric size are common. This microfacies is very widespread (Fig. 3) both in Castillo the Mula stratigraphic section (at about 2 m, and corresponding to lithofacies F1) and in the Prado Mayor Section (at about 5 m, and corresponding to lithofacies A2 to A4) and in the Malvariche Section (with a thickness of more than 25 m, and corresponding to lithofacies E+F and the lowermost part of G). These lithofacies are made of amalgamated biocalcarenes with algae, biomicritic limestones with very abundant LFB (Table 1, Fig. 3).

Mf9 - Nummulitid packstone-wackestone (Table 2, Figs. 4, 5). This microfacies, moderately sorted, is mainly composed of a biocalcarenic packstone-wackestone constituted by abundant A and B lenticular tests of *Nummulites* (25-30%) and common *Assilina* (10%), operculiniform *Assilina* (5%), *Amphistegina* (5%), small rotaliids (5-10%), crustose coralline algae (5-10%), and fragments of molluscs (5-10%) and echinoid plates (5-10%). Isolated elements of *Glomalveolina* (5%), miliolids (2-3%), discorbids (2-3%) and textulariids (2-3%) are also present. This microfacies is very widespread (Fig. 3), being present in the stratigraphic section Castillo de Mula (at about 2 m, and corresponding to lithofacies F2), in the Prado Mayor section (at about 2 m, and corresponding to lithofacies A1), and in the Malvariche section (with a thickness of more than 20 m, and always corresponding to lithofacies E+F). These lithofacies are made of amalgamated biocalcarenes, decametric-scale limestones with microconglomerate bands containing quartzitic clasts, and limestones with very abundant LFB (Table 1, Fig. 3).

Mf10 - Flat nummulitid, orthophragminid and solitary coral packstone (Table 2, Figs. 4, 5). This microfacies, moderately sorted, shows abundant A and B flat tests of *Nummulites* (30-35%), *Assilina* (5-10%) and *Discocyclus* (15-20%), common operculiniform *Assilina* (2-3%), solitary corals (15%), turrillate gastropods (5%), pelecypods (5%), serpulid worm tubes (2-3%) and echinoid spines (5%). Small benthic foraminifera such as miliolids, bolivinids, textulariids, valvulinids, planktonic foraminifera and ostracods are other biogenic components (10%). This microfacies is only present in stratigraphic section 2 (Castillo de Mula) with a reduced thickness

of about 2 m and corresponds to lithofacies F2 made of amalgamated biocalcarenes (Table 1, Fig. 3).

Mf11 - Alveolinid, soritid and miliolid packstone (Table 2, Figs. 6, 7). This microfacies, moderately sorted, is composed of a biocalcarene packstone constituted mainly by porcelaneous foraminifera tests such as *Alveolina* (15-25%), *Orbitolites* (10-15%) and small miliolids (5-10%), but also by abundant discorbids (2-3%) and pellets (5%). *Nummulites* (5-10%), operculiniform *Assilina* (5%), *Amphistegina* (2-3%), rotaliids (2-3%), textulariids (2-3%), and echinoid plates and spines (2-3%) are other common biogenic components. Some components such as dasyclads, crustose coralline fragments, isolated *Distichoplax biserialis* specimens, serpulid worm tubes and quartz grains are also present (10-15%). This microfacies is present in the section at Prado Mayor (at about 2 m, and corresponding to lithofacies A1) and is also very common in the Malvariche section (Fig. 3). In this latter section the microfacies is very widespread occurring at three stratigraphic levels of the column: in the bottom part (corresponding to lithofacies A) with a thickness of 2 m, further upwards (corresponding to lithofacies D) with a thickness of about 10 m, and in the upper part of the column (corresponding to lithofacies G) with a thickness of 2 m. These lithofacies are made of fine limestones, biocalcarenes and micritic limestones with very frequent LFB (Table 1, Fig. 3).

Mf12 - Alveolinid and *Nummulites* packstone-grainstone (Table 2, Figs. 6, 7). This microfacies, moderately to well sorted, is composed of a packstone-grainstone texture with rounded coralline algae and acervulinid fragments. Pellets are also abundant as well as grains of abraded and rounded specimens of *Alveolina* (10-15%), *Glomalveolina* (10%) and *Nummulites* (10-15%). Other common foraminifera are represented by miliolids (5%), rotaliids (5%), discorbids (2-3%), textulariids (2-3%) and *Solenomeris* remains (10%). Geniculate and non-geniculate coralline algae (included specimens of *Distichoplax biserialis*) (5-10%), dasycladacean algae (2-3%), gastropods (5%) and echinoid plates (5%) with syntaxial cement

are common. Other skeletal components observed are isolated specimens of operculiniform *Assilina* (2-3%) and some rounded lithoclasts (5%). The common presence of sparitic cement between grains is noted. This microfacies (Fig. 3) is present in the section at Prado Mayor (at about 5 m and, corresponding to lithofacies A4 and G) and also in the Malvariche section (almost 10 m thick, and corresponding to lithofacies G). These lithofacies are made of micritic limestones characterized by poor fossil content, usually miliolids (Table 1, Fig. 3).

Mf13 - Gastropod and ostracod calcisiltitic wackestone (Table 2, Figs. 6, 7). This well sorted microfacies is composed of calcareous fine-grained components in a wackestone texture that contains a low diversity biogenic assemblage constituted by abundant thin-walled ostracods (5-10%) and pellets (10-15%), and common gastropods (10%) and textulariids (5-10%). Isolate grains of glauconite have been also recognized. This microfacies in the field has been included into litho-biofacies H3 (Table 1), and shows abundant mm- to cm-scale gastropod tests, and common isolated cm- to dm-scale ostreid valves. This microfacies is dominant in the stratigraphic section at Prado Mayor (more than 30 m thick, and corresponding to lithofacies H3) and is also very common in the Malvariche section (Fig. 3). In this latter section, the microfacies is present at two stratigraphic levels: at the bottom (corresponding to lithofacies B and C) with a thickness of 1 m, and with more than 5 m of thickness in the uppermost part of the column (corresponding to lithofacies G). These lithofacies are made of marls, clays and micritic limestones with gastropods (Table 1, Fig. 3).

5. Discussion

5.1. Litho- and biofacies interpretation

In this section a paleoenvironmental interpretation will be provided for the Paleocene and for the early Eocene depositional environments. Platform sedimentary realms have been proposed taking into account the above described litho- and microfacies (*Mf1* to *Mf13*).

During the Paleocene several platform sedimentary realms can be deduced from the studied sediments. The Paleocene ramp is recognized based on microfacies *Mf1* to *Mf6*. The inner ramp is represented by *Mf1* to *Mf3*, *Mf4* represents the transition to middle ramp, the frank middle ramp is represented by *Mf5*, while the outer ramp is represented by *Mf6*.

Mf1 (*Quartzsiltite to quartzarenite with gastropods*) shows sedimentary characters (poorly stratified fine to coarse grained lenticular beds, with parallel lamination at the top, arranged in shallowing upward para-sequence) referable to a shallow water marine platform. In general, the microfacies indicates restricted marine environments near the continent, in a low energy context with sporadic detritic alluvial to fluvial supply. Common small gastropods and discorbids (Table 2) suggest the presence of vegetation (Beavington-Penney et al., 2004; Reich et al., 2015), while the association of hyaline small benthic foraminifera (r-strategists) indicates unstable environmental conditions with a notable presence of inorganic nutrients (Hottinger, 1997; Hallock, 1988a). Dasyclads, although scarce, indicate shallow marine conditions in a protected context and the presence of reworked *Microcodium*, regarded as a soil biogenic calcification in non-marine substrates in stationar semi-arid conditions, as the recent mediterranean climate (Kosir, 2004). Thus, this assemblage indicates a shallow euphotic and meso- to eutrophic marine environment with low energy conditions in a restricted inner ramp setting. The presence of vegetation (plant/algal) in the vicinity is not ruled out. Reworked *Microcodium* indicates occasional influences from the continent that can increase quartz and nutrient levels, suggesting a supratidal-intertidal environmental context (e.g., Afzal et al., 2011). Thus, the set of these features, mainly resulting from the biofacies, indicates a shallow euphotic and meso-eutrophic marine environment with low energy conditions in a restricted inner ramp

setting. **Mf2** (*Rhodolith and coral floatstone-packstone*) is characterized by the presence of terrestrial-sourced quartz grains and reworked 'corn-cob' *Microcodium* grains that indicate the proximity of euphotic marine conditions which are reflected by the predominance of porcelaneous foraminifera; and also small miliolids and complex ones as *Idalina* are euryhaline and permanently motile epiphytic forms living in shallow protected lagoonal environments and that thrive in areas with marine vegetation (Tomás et al., 2016). Their abundance besides the common presence of gastropods and geniculate coralline algae, sometimes as epiphytes in warm to temperate seagrass (Reich et al., 2015), supports interpretation of a lagoon paleoenvironment. Furthermore, the green algae content (dasyclads and codials) indicates a protected low energy marine environment (Granier, 2012); lunulitiform colonies of bryozoans are also common on loose sandy substrates (Moissette, 2000). In addition, the heterotrophic assemblage of suspension and/or deposit feeder organisms (miliolids, hyaline small benthic foraminifera, erect colonies of bryozoans, and echinoid remains), and quartz content, can be explained in mesotrophic conditions by the occasional input of inorganic nutrients from the continent (Tomás et al., 2016). The presence of coral pebbles encrusted by non-geniculate coralline algae, with a debris of crustose and geniculate coralline algae and other described biogenic components, indicate a photozoan to heterozoan warm-water assemblage (Westphal et al., 2010; Michel et al., 2018) in a protected marine lagoon beside a coralline patch reef and rodophyta crust environment in inner ramp settings (Afzal et al., 2011). **Mf3** (*Coral and red algae grainstone-packstone*) consists of grainstone-packstone microfacies with reworked, abraded and rounded bioclasts from highly euphotic marine environments, suggesting moderate to high energy environments (such as shoal or channel deposits) with a partially hardened substrate near the coral patch reef or rodophyta crust in a mesotrophic inner ramp setting (Afzal et al., 2011; Sarkar, 2015). On the other hand, micritization processes are responsible for development of micritic envelopes, often referred in marine conditions to a high nutrient content (Hallock, 1988b).

Mf4 (*Crustose coralline algae and Solenomeris bindstone*) is characterized by both columnar shape and dichotomous open-branching type rhodoliths indicating moderate water energy or deep water ‘coralligène’ settings (Bosence, 1991). The dominance of macroids of *Solenomeris* can be explained by an ecological change as light reduction in a deepening context (Varrone and d’Atri, 2007). The abundance of small miliolids and common geniculate coralline algae, green algae and small benthic foraminifera (textulariids, rotaliids) indicates mesotrophic conditions in a low energy shallow marine setting as a distal inner ramp to proximal middle ramp environment (Afzal et al., 2011; Sarkar, 2015). The presence of common peysonelliacean *Polystrata alba*, characteristic of soft-substrate in conditions of low input of sediments and lack of reworking processes in relative deep marine habitats (Bassi, 1998; Rasser, 2001; Jauhri et al., 2005), agrees with the presented data. Lithology and significant microfacies assemblage suggest a protected segment of a coral reef frame (back-reef lagoon) or a rodophyta crust (maërl) environment.

The Paleocene middle ramp is recognized with **Mf5** (*Coral and Solenomeris floatstone-packstone*). It has been identified in the Castillo de Mula section (Interval P3, upper Paleocene, Log 2, Table 1). The lithofacies and its sedimentary structures (poor stratification, fine to coarse grain size, occasional interlayers of silty-sandy marls, lenticular beds with vertical thickness ranging from 10-20 cm to 1 m) are compatible with a high energy marine environment. The microfacies are characterized by the presence of adeoniform bryozoan colonies and can be indicative of deeper marine conditions than previous microfacies on a mainly sandy bottom, reflected by the presence of lunulitiform bryozoan colonies (Moissette, 2000). Although the dominance of grazer and filter-feeding organisms suggests eutrophic conditions (Afzal et al., 2011), the common presence of oligotrophic LBF (miscellanids) could reduce nutrient levels to mesotrophic conditions in a mesophotic marine middle ramp (Hottinger, 1983, 1997). The presence of Dasycladales, probably reworked, has been registered with very low abundance (one

or two times in all the thin sections). Litho- and biofacies can be interpreted as related to a reef slope environment and equivalent to the ramp slope context of Serra-Kiel et al. (1991) and Pomar (2001a, b).

The Paleocene outer ramp is recognized in *Mf6* (*Quartzarenitic wackestone with planktonic foraminifera*). This microfacies has been recognized in the previously reported Interval P3 (Log 2). The quartzarenitic beds are probably originated by occasional turbidite flows triggered by storms and exceptional continental water flows. Planktonic foraminifers are common while LBF are missing in the microfacies assemblage. Dasycladales, probably reworked, has been registered with very low abundance (a few times in all the thin sections). It indicates an oligophotic and low energy open marine context in deeper environments than the previous microfacies, corresponding to the open shelf or outer ramp of Serra-Kiel et al. (1991), Pomar (2001a, b) or Afzal et al. (2011).

During the early Eocene several platform sedimentary realms from the inner and middle ramp can be deduced from the studied sediments. The inner ramp is represented by *Mf13*, *Mf12* and *Mf11*, arranged from proximal to distal, while the middle ramp is represented by *Mf8*, *Mf7*, *Mf9* and *Mf10*, from proximal to distal.

Mf13 (*Gastropod and ostracod calcisiltitic wackestone*) is made of homogeneous silty-sand mudstones with occasional decimetric beds of arenites and micritic limestones containing freshwater gastropods indicating a transitional environment. The microfacies shows a dominant heterotrophic association, which suggests meso- to eutrophic conditions in an unstable depositional setting with possible continental terrigenous supplies. The presence of a plant cover on the bottom is not ruled out by the abundant presence of small gastropods, which can be numerous in seagrass meadows (Beavington-Penney et al., 2004), and several families of them are considered as indirect paleo-seagrass indicators (Reich et al., 2015). *Mf12* (*Alveolinid and Nummulite packstone-grainstone*) is represented by amalgamated blackish-gray and brownish

micritic limestones. The microfacies consists of packstone-grainstone with numerous abraded and rounded skeletal grains of alveolinids or geniculate red algae, suggesting a high energy shoal environment in the inner ramp (Pomar, 2001b; Afzal et al., 2011; Sarkar, 2015). Mixing of deeper fauna as *Nummulites* and operculiniform *Assilina* can be explained by reworking to marine distal zones (middle ramp) during storm events in euphotic upper subtidal conditions. **Mf11** (*Alveolinid, soritid and miliolid packstone*) consists of massive micritic limestones that in the upper part shows frequent up to 20-30 cm large frondescent corals. The abundance of porcelaneous LBF indicates euphotic shallow marine settings in moderately oligotrophic upper subtidal environments (Hottinger, 1997). Common epiphitic forms (*Orbitolites*, discorbids) suggest the presence of submarine vegetation in the infralittoral context. Nummulitids indicate deeper marine conditions and can be deposited in an inner ramp seagrass where the mixed fauna can be explained by storm events that provides hyaline LBF tests from deeper environments. Moreover, Beavington-Penney et al. (2004) also describe A-form *Nummulites* populations in sea grass beds. In summary, all the observed features indicate a middle ramp sea-grass euphotic lower subtidal environment.

The early Eocene middle ramp is represented by **Mf8**, **Mf7**, **Mf9** and **Mf10**, arranged from proximal to distal. **Mf8** (*Coral, acervulinid macroid and rhodolith bindstone-floatstone*) shows mostly biogenic components and indicates warm, shallow and euphotic marine conditions. Abundant *Distichoplax biserialis* suggests a protected lagoon related to reef environments (Muftah, 2010). However, the binding structures of crustose coralline and the encrusting foraminifera *Solenomeris* are numerous; the latter with a depth distribution which does not depend on light, indicating habitats deeper than coral environments. The warty to lumpy growth form of rhodoliths and the high content in bryozoans suggest mesophotic conditions, in middle ramp environments (Moissette, 2000). The presence of abundant pellets, isolated reworked alveolinids and rotaliids from shallower sectors of the shelf can be explained as a result of

mixing by the effect of storms just above the fair weather wave base (fwwb) as in the Macroïd Boundstone Microfacies type of Scheibner et al. (2007). In addition, the heterotrophic assemblage is related to the recycling of sediments in oligo- to mesotrophic habitats in a marine middle ramp environment. The above exposed indicates that it can be attributed to a proximal middle ramp coral-maërl mesophotic environment. **Mf7** (*Rhodolith, nummulitid and orthophragminid floatstone*) consists of massive amalgamated, poorly stratified, fine to medium grained biocalcarenites that are compatible with a channelized marine environment. The microfacies shows an abundance of nummulitids and orthophragminids that are typical of mesophotic and oligotrophic conditions in deeper middle ramp environments (Hottinger, 1997; Geel, 2000). Encrusting action by crustose coralline red algae and/or acervulinds (*Solenomeris* and others) has been described in sandy marine bottoms associated with winter storms, which periodically can turn over the tests to form rhodoliths and macroïds. The additional presence of a widespread heterotrophic biogenic assemblage supports the idea of a mesophotic and oligo- to mesotrophic marine conditions at a middle ramp maërl environment. **Mf9** (*Nummulitid packstone-wackestone*) shows the dominance of lenticular nummulitids in packstone-wackestone beds containing well represented populations of microspheric and megalospheric specimens. These are indicative of accumulations in situ in optimal parts of the area inhabited by these organisms, characterizing marine mesophotic and oligotrophic conditions in the upper part of the middle ramp (Hottinger, 1997; Geel, 2000). Nevertheless, mixing of flattened tests of *Assilina* and operculiniform *Assilina* could indicate an intermediate depth into the middle ramp environment. **Mf10** (*Flat nummulitid, orthophragminid and solitary coral packstone*) is characterized by a well represented populations of LBF and the presence of both A and B morphotypes. This suggests optimal oligotrophic stable conditions in the most favourable parts of the habitat (Hottinger, 1997; Geel, 2000). The LBF assemblage, dominated by flattened nummulitids and orthophragminids, indicates the lowermost mesophotic area in a distal middle

ramp environment (Hottinger, 1997). The additional presence of planktonic foraminifera indicates open sea conditions into the photic zone, like the solitary corals, hampered of algal symbionts. Solitary corals usually thrive in soft fine-grained substrates both in shallow turbid-water habitats (Sanders and Baron-Szabo, 2008) and in deeper habitats in meso- to oligophotic marine environments (Serra-Kiel et al., 2003; Astibia et al., 2014).

5.2. Paleoenvironmental evolution

The presence of a significant stratigraphic discontinuity at the Paleocene-Eocene boundary that covers the entire lower part of the early Eocene (Ilerdian) for a time span of almost 3 Ma allowed subdivision of the stratigraphic record into separate Paleocene and Cuisian stratigraphic sequences. Moreover, the presence of different features of the marine platforms and main fossil groups can inform on the paleoenvironmental evolution of the stratigraphic sequences.

5.2.1. Paleocene paleoenvironmental evolution

In the Doñana stratigraphic section two possible minor unconformities have been recognized. The first, in the middle portion of the succession, separates restricted tidal from lagoonal deposits (Fig. 5) interpretable as a basal transgressive surface. The second sequence boundary, in the upper part of the succession, coincides with the Danian-Selandian boundary and could represent a major break in the sedimentation related to the Mid-Paleocene Unconformity (MPU) recognized also in the Pyrenean realm (Baceta et al., 2004, 2005). The Selandian succession is characteristic of an inner ramp shoal environment passing upwards to a distal inner to middle ramp maërl context. The upper part of the Paleocene (Thanetian deposits, Log 2, Fig. 5) includes most of the marine sediments of the area, deposited in a middle to outer ramp setting.

In the Prado Mayor stratigraphic section, Paleocene continental *Garumnian*-like facies (Martín-Martín et al., 1998) consisting of continental reddish beds with in situ *Microcodium* are exposed marginally. Also in the Doñana and Castillo de Mula reworked fragments of *Microcodium* are found in the marine sediments due to sudden floods from the continent. These deposits have not been sampled for thin section studies since only clays and marls crop out. Nevertheless, the existence of these continental facies indicates that the area of Sierra Espuña in the Paleocene had emerged and was characterized by continental fluvial-alluvial deposits. The presence of *Microcodium*, a structure related to calcification of plants roots in soil with a warm climate gives information about climate during this period.

The environmental evolution of the reconstructed Paleocene history is schematized in Figure 8, accompanied by selected images of the relevant microfacies. The fossiliferous assemblage described in the Paleocene deposits only outcropping in the deeper Mula Basin, constitutes a mixture of photozoan and heterotrophic biogenic elements that alternate in the stratigraphic succession. This could suggest oligotrophic settings at low latitudes characterized by alternating periods of supply of nutrients during warm to temperate settings ($\sim 25^\circ$) as in the transition of foramol to chlorozoan factories of Lees and Buller (1972), the chlorozoan to chloralgal setting proposed by Carannante et al. (1988), or as the warm temperate biogeographic province proposed by Betzler et al. (1997).

5.2.2. Early Eocene paleoenvironmental evolution

As commented above, only the Cuisian period is preserved and/or deposited in the study area. In the Castillo de Mula Section (Fig. 5), the deposits associated with this period are arranged in a relative shallowing succession that evolves from a mesophotic middle ramp maërl environment to a shallower coral-maërl marine environment in the proximal part of the middle ramp. In its

upper part a deepening succession deposited in a ramp environment from mesophotic middle ramp to a meso- to oligophotic distal middle ramp occurs. In the case of the Prado Mayor-Malvariche sector (Fig. 5), the lower portion of the Espuña Fm (Sierra Espuña) evolves upwards to the Valdelaparra Fm, suggesting a transgressive-regressive depositional cycle. The lowermost beds show a biogenic assemblage with evident seagrass meadows (*Orbitolites*, discorbids and A-form *Nummulites*), which suggests an inner to middle ramp environment; the middle portion corresponds to a mesophotic middle ramp. The upper portion shows a shallowing up succession evolving from a middle ramp maërl to an inner ramp protected lagoon passing through a shallow marine seagrass and a high energy shoal environment in the inner ramp. In Sierra Espuña a transgressive-regressive sedimentary evolution is represented, showing a similar evolution from an inner ramp shallow marine seagrass environment to a middle ramp and to a distal middle ramp maërl environment. The upper portion of the succession includes deposits related to high energy realms (shoals) in inner ramp environments passing upwards to shallow marine protected or marshy environments.

The environmental evolution of the reconstructed early Eocene history is schematized in Figure 9 accompanied by selected images of the related microfacies.

The fossiliferous assemblage described in the early Eocene deposits of Sierra Espuña-Mula shows a mixing of photozoan and heterotrophic components. Photozoan assemblage suggests euphotic to oligophotic environments in oligotrophic marine warm-water settings at low to middle latitudes. A heterotrophic assemblage can occur as associated to the photozoan or as a unique association, suggesting meso- to eutrophic steps that could be related with periods of nutrient availability or upwelling settings in warm to temperate regions at low to middle latitudes (~25°). Equivalent models have been described at similar or somewhat lower latitudes in the late Ypresian El Garia/Jdeir/El Haria Formation from Tunisia and Libya (Loucks et al., 1998; Racey et al., 2001; Jorry et al., 2006), and in the early Eocene Jafnayn Formation (Tomás et al., 2016)

and the middle Eocene Seeb Formation from Oman (Racey, 2001). Both cases, in which there is an extensive development of LBF-rich facies suggesting a continuous and progressive deepening ramp in oligotrophic conditions, have defined several facies belts based on the fabrics and the depth-controlled distribution of LBF and, from them, the inferred presence of sea-grass and maërl environments, as proposed here.

5.2.3. *Proposed paleoenvironmental and paleogeographic models for the Paleocene-early Eocene*

All the above reported evidence that the materials constituting the Paleocene Mula Fm were deposited with a transgressive trend in a shallow marine carbonate ramp setting (in the Mula Basin area) with occasional siliciclastic contributions from the continent. This platform shows a mixing of photozoan and heterotrophic biogenic elements of inner to outer ramp environments proper of a warm temperate biogeographic province, and should be connected to emerged areas (in the Sierra Espuña area) similarly with a warm climate as indicated by the occurrence of *Garumnian*-like facies with *Microcodium* (see Martín-Martín, 1996; Martín-Martín et al., 1998). A paleogeographic representation is shown in Figure 10A.

In the case of the early Eocene (Fig. 10B) a rapid transgression (at the bottom) followed by a regressive sedimentary trend are represented, showing sedimentary environments that are similar to those of the Paleocene. Transgressive evolution from an inner ramp shallow marine seagrass environment to a middle ramp, and to a distal middle ramp maërl environment is recognized, followed by a regressive trend characterized by high energy realms (shoal) in inner ramp environments passing upwards into shallow marine protected or marshy environments.

5.3. *Comparison with other sectors*

The Paleocene-early Eocene paleoenvironmental evolution of the studied area is compared with other Tethyan sectors, starting from the Betic and Rifian sectors, in order to obtain general constraints for the evolution of the Western Tethys platforms during the considered time span.

5.3.1. Betic and Rifian sectors

Paleocene-early Eocene shallow marine sedimentation is known in the Betic Cordillera, as well as in the Moroccan Rif, even if specific studies on platform deposits are rare. A paleogeographic sketch map near the Cretaceous-Cenozoic boundary (70 Ma) is presented in Figure 10A where the studied sector (Sierra Espuña) and the compared areas are reported. The early Paleogene paleogeographic position of the study area was at low latitudes ($\sim 25^\circ$ N) in the westernmost Tethys (meridian $\sim 10^\circ$ W), at the transition with the Atlantic domain (Scheibner and Speijer, 2008). The Sierra Espuña succession shows similarities to coeval units defined by Chacón and Martín-Chivelet (1999, 2005), Martín-Chivelet and Chacón (2007) and Pujalte et al. (2010) in the Prebetic located at about the latitude 30° N and in the westernmost Tethys, between longitude 10° - 15° W (Fig. 11A: 2 and 3; 11B). The lower Eocene shallow marine deposits are represented in the Prebetic (SE Spain) (Fig. 11A: 2, 11B) about at latitude 33° N (Martín-Martín et al., 2018a,b), at about longitude 10° W (Geel, 2000). In this case the sedimentary trend indicates a middle to inner ramp environment, in good agreement with the lower Eocene deposits of the Sierra Espuña.

5.3.2. Other Tethyan sectors

In most of the Tethyan and peripheral Atlantic areas, Paleocene-lower Eocene carbonate platforms deposits belonging to the Pyrenean Chain (Pomar et al., 2017; and references therein) are characterized by shallow marine carbonates related to coral reefs located on the marginal platform or the slope (Baceta et al., 2004, 2005; Robador, 2005; Scheibner and Speijer, 2008; Pomar et al., 2017). In particular, Baceta et al. (2004, 2005) and Robador (2005) recognized and dated four Paleocene depositional units, bounded by unconformities: (a) lower Danian (biozone SBZ 2); (b) upper Danian (SBZ 2); (c) Selandian-lower Thanetian (SBZ 3); and (d) upper Thanetian (SBZ 4). Several unconformities were also described between the Danian and Selandian units. In this realm, the lower Eocene deposits are represented by two carbonate platform episodes bounded by unconformities, corresponding respectively to the biozones SBZ 5 and SBZ 6 LBF of Serra-Kiel et al. (1998b), and characterized by the dominance of larger foraminifera *Alveolina* ('Alveolina Limestone') and the absence of coral reefs.

Scheibner and Speijer (2008) addressed studies on different Tethyan sectors, highlighting three stages in the evolution of carbonate platforms: (a) coral-algal platform dominated by coral reefs, corresponding to the SBZ 3 LBF Zone of Serra-Kiel et al. (1998b); (b) transitional coral-algal to larger foraminifera platform (with coral reefs in mid latitudes and larger foraminifera in low latitudes), corresponding to the SBZ 4 Zone of Serra-Kiel et al. (1998b); and (c) larger foraminifera platform (dominated by larger foraminifera in all latitudes), corresponding to the SBZ 5-6 of Serra-Kiel et al. (1998b).

Pomar et al. (2017) also consider for the same time interval three main production stages for shallow marine carbonate platforms deposits of the central-western Mediterranean Tethys: (a) Danian, with small isolated patch reefs to large reef complexes, mainly located on the platform/slope margin; (b) Selandian-Thanetian, with algal-dominated constructions, located landwards with respect to previous Paleocene buildups, and (c) early Eocene (Ilerdian, before the early Eocene Climatic Optimum), when coral buildups reduced in size and diversity with the

rising temperatures of this interval, and LBF thrived and expanded in the homoclinal marine ramps extending from the littoral to the deep oligophotic zone. After extinction accounted at the Cretaceous-Paleogene boundary, Paleocene foraminiferal diversification is found in the area of Lake Van (SW Turkey), being taxa of the foraminiferal subfamily Lockhartiinae, the best represented among the marine shallow benthic communities. This gives rise to the so-called 'Lockhartia community' (Hottinger, 2014) characterized by numerous elements of this rotaliid subfamily as *Lockhartia*, *Dictyoconoides* and *Sakesaria*. Other more cosmopolitan K-strategist foraminifera could be found associated with them, such as miscellanids, alveolinids, orbitolitids, nummulitids and orthophragminids, with a low diversity and abundance, especially in the central-eastern Tethys. The genres *Ranikothalia* and *Assilina* thrived in central-eastern Tethys (Scheibner and Speijer, 2008; Afzal et al., 2011; Sarkar, 2015; Li et al., 2017) but also, with lower diversity, in the western Adriatic platform (Vecsei and Moussavian, 1997; Zamagni et al., 2012), Western Carpathians (Bucek and Köhler, 2017) and Pyrenean realm (Tosquella et al., 1998, and references therein). The 'Lockhartia community' continued to dominate the foraminiferal assemblage of shallow marine environments during the early-middle Eocene in the central-eastern Tethys extending from south Turkey to the easternmost Tethys margin (i.e., Iraq, Iran, Afghanistan, India and south Tibet). Similar deposits are also represented in east Africa from Egypt to Somalia, through the Arabian Peninsula, but are not recognized in the Western Tethys in North Africa, Adriatic-Hellenic region, Pyrenean domain and Betic Cordillera (Hottinger, 2014).

In summary, during most of the Paleocene (SBZ1-3 from Serra-Kiel et al., 1998b and Platform Stage 1 of Scheibner and Speijer, 2008), the northern Mediterranean Tethys platforms were located at the middle paleolatitudes. Platforms in the Hellenian-Anatolian Arc, Adriatic and peripheral Atlantic regions were characterized by coral-reef and coralgall facies (i.e., Baceta et al., 2005; Robador, 2005; Scheibner and Speijer, 2008; Drobne et al., 2009; Zamagni et al., 2012;

Pomar et al., 2017). This time span, coinciding with the Global Community Maturation Cycle-1 and lower part of the Global Community Maturation Cycle-2 of Hottinger (2001), is characterized by low abundance and diversity of LBF, with colonial corals and coralline red algae being some of the more abundant components in these environments. Only in the latest Thanetian ('Assilina beds' of Baceta et al., 2005; SBZ 4, Platform Stage 2, and upper part of the Global Community Maturation Cycle-2) and, mainly, at the beginning of the Ypresian (SBZ 5-6, Platform Stage 3 and Global Community Maturation Cycle-3), when conditions change, does LBF colonize and dominate these environments, ecologically displacing the dominant coral-reef biofacies. The explanation of this is still under discussion (Pujalte et al., 2003; Baceta et al., 2005; Scheibner et al., 2005; Scheibner and Speijer, 2008; Pomar et al., 2017). During the remaining portion of the early Eocene, coinciding with the EECO interval (52-50 My, Zachos et al., 2001), the LBF increase in size and dominate shallow marine platforms, while coral reefs are restricted to small reef patches without forming any large coral buildups.

During the Paleocene, in the southern rim of westernmost Tethys, the shallow marine platforms at intermediate paleolatitudes between 20-30°N, as in North Atlas Platform (Morocco and Tunisia), do not develop coral-reefs and biogenic associations. These platforms are characterized by oyster reefs at Platform Stage 1 (biozone SBZ 3), and by oyster reefs, bryozoans and coralline algae at Platform Stage 2 (SBZ 4), while the early Eocene sedimentation lacks LBF (Scheibner and Speijer, 2008). The platforms in the African region, at paleolatitudes below 20°N (Libya, Egypt, Oman, Yemen) are characterized during the early Paleocene (Platform Stage 1, SBZ 1-3) by corallgal biofacies or small coral reefs (Global Community Maturation Cycle-1 and lower part of the Global Community Maturation Cycle-2). The late Paleocene sedimentation (Platform Stage 2, SBZ 4) in Libyan Sirte Basin and Egyptian Western Desert is characterized by small coral reefs, and in other places as well as the Egyptian Galala Mountains by the dominance of LBF (upper part of the Global Community Maturation Cycle-2).

Finally, early Eocene sedimentation in the southern Tethys margin (SBZ 5-6, Platform Stage 3) is characterized, as in the northern margin, by the dominance of LBF, as a constant biological event recognizable on all marine platforms across Tethys (Global Community Maturation Cycle-3).

5.4. Paleocene-lower Eocene carbonate platforms of the westernmost Tethys

During the early Paleogene, the Sierra Espuña area would be at a latitude close to 25° N (Fig. 11A). During the Paleocene, the development of shallow marine biofacies also occurred in a ramp-like context in the Sierra Espuña-Mula Basin but lacking developed reef structures, as in other western and southern Tethyan areas. Sedimentary biofacies are similar to those described in other sectors of the Tethys, although the association of LBF is poorly represented, showing low abundance and diversity. Genera *Ranikothalia* and *Assilina*, very common in central and eastern Tethys, are absent in the studied stratigraphic sections. By contrast coral-algal biofacies were widely developed in Sierra Espuña-Mula Basin, with some coral remains, abundant coralline algae, common green algae taxa, small foraminifera and encrusting foraminifera dominated by *Solenomeris* and other acervulinid and planorbulinid genera. This suggests that coral-algal biofacies could be very widespread in westernmost Tethys.

During the early Eocene widespread distribution of LBF and the concomitant disappearance of coral constructions took place (Martín-Martín et al., 2001). Nevertheless, abundant corals have been observed in the lower Cuisian beds of the Sierra Espuña, indicating that in the westernmost Tethys at these latitudes, coral continued to develop as opposed to similar latitudes of other southern and western Tethyan areas. In the Atlas platform (Morocco and Tunisia), biogenic benthic associations are characterized by oyster reefs, coralline algae and some

heterotrophic elements as bryozoans, suggesting eutrophic conditions with respect to contemporaneous platforms of the northern margin of the Mediterranean Tethys.

6. Conclusions

The Mula Basin is characterized by Paleocene-lower Eocene sediments (marls with alternating calcarenites) deposited in shallow to deep marine conditions. Instead, in the Sierra Espuña area, the Paleocene sediments are very limited and mainly reflect fluvial-alluvial environments. At Sierra Espuña the lower Eocene sediments are well developed and mainly represented by two stratigraphic formations (limestones and calcarenites with larger foraminifera; marls and micritic limestones with gastropods) indicating platform and lagoon environments, respectively.

Paleocene microfacies of the Mula Basin show a mixing of photozoan and heterotrophic biogenic elements varying in space and time indicating the evolution from inner to outer ramp settings with the presence of corals. Other photozoan elements (crustose and geniculate coralline red algae, codiacean and dasycladal green algae, and symbiont-bearing LFB) are also present, suggesting an oligotrophic warm marine setting. The presence of heterotrophic elements indicates periods of nutrient supply in warm to temperate climates, as in the transition of foramol to chlorozoan factories, chlorozoan to chloralgal zone, and the warm temperate biogeographic province. The above-mentioned marine platform realms should be connected with emerged areas (Sierra Espuña) characterized by a warm climate, as indicated by the occurrence of *Garumnian*-like biofacies with *Microcodium*.

The lower Eocene microfacies shows a mixing of photozoan (LBF, calcareous red and green algae and hermatypic corals) and heterotrophic biogenic elements (large encrusting, small benthic and planktonic foraminifers, ostracods, bryozoans, molluscs, echinoids and serpulid worm tubes)

and suggest an inner to middle ramp coral-maërl environment. The occasional presence of coral phaceloid colonies is noticeable by their general absence from the onset of the Eocene.

The Paleocene depositional trend shows similarities with coeval units of the Prebetic domain, while the studied lower Eocene succession differs from this domain (in Murcia and Alicante provinces) because in some cases the preservation of the Ilerdian indicates an apparent stratigraphic continuity. In other cases, hemipelagites containing reworked platform fossils in slope environments have been observed. The platform stratigraphic sections and the transitional to hemipelagic ones from the Prebetic, show a similar fossil assemblage to coeval sediments in the Sierra Espuña area, with abundant shallow marine platform LBF, coralline red algae and echinoids, also related to inner to middle ramp environments.

Early Paleogene LFB assemblages (shallow marine environments) in the study area differ from the coeval rotaliid 'Lockhartia community' consisting of the dominance of alveolinids, nummulitids and orthophragminids.

The studied Paleocene-lower Eocene stratigraphic sequences characterizing the evolution of carbonate platforms have been compared with similar (but not identical) successions described elsewhere in the Pyrenean realm. The lowermost Eocene deposits, represented by two carbonate platform episodes, show the dominance of the larger foraminifera *Alveolina* (SBZ5-6), not represented in Sierra Espuña-Mula Basin. Here, an early Ypresian (Ilerdian) hiatus existed until the late Ypresian (Cuisian), whose origin can be attributed to the drying of ocean due to a global warming during this period, or to local and/or regional tectonics.

During most of the Paleocene, the Sierra Espuña-Mula Basin would be located near 25°N between the northern temperate Pyrenean realm and the intermediate temperature one of Tunisia, roughly corresponding to the latitude of the northern margin of Morocco (African Atlas). At the same time, the development of shallow marine litho- and biofacies in the study area occurs in a ramp-like context, with a coralgall factory but lacking of significant coral-reef structures; as

opposed to what is found in many localities of the northern margin of the Mediterranean Tethys, especially in the Pyrenean area. The association of LBF is poorly represented in this area showing a low abundance and diversity. Only some groups like complex miliolids (*Idalina*), miscellanids and rotaliids are present. *Ranikothalia* and *Assilina* genera thrived in the central-eastern Tethys, but were rare in the Prebetic domain and absent in the Sierra Espuña-Mula Basin. During the early Eocene an expansion of the LBF took place together with the disappearance of coral constructions during the late Ypresian (Cuisian). However, coral fragments and colonies have been observed in the lower Cuisian (Sierra Espuña area). This indicates that coral continued to develop as opposed to what is observed at similar latitudes in other zones of the southern and western Tethys (e.g., Atlas platform in Morocco and Tunisia).

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Figure and Table captions

Fig. 1. (A) Location of the study area in the Murcia Province (SE Spain); (B) Western mediterranean alpine chains with location of the Murcia Province in the Betic Cordillera; (C) Paleogeographic sketch at the late Cretaceous of the Western Mediterranean area (after Guerrero and Martín-Martín, 2014) with location of the study area (SE), Pyrenean domain (Pi), Prebetic domain (Pb), Rifian domain (Ri), Moroccan domain (Mo) and Tunisian domain (Tu); (D) Geological map of the Sierra Espuña-Mula Basin area with location of the geological cross section in E and the studied stratigraphic sections (1 to 4); (E) Geological cross section.

Fig. 2. Stratigraphic framework of the Cenozoic succession of the Sierra Espuña-Mula Basin area.

Fig. 3. Studied stratigraphic sections represented as columns and location of the studied samples.

Fig. 4. Photomicrographs of microfacies of the Stratigraphic Sections 1 (Doñana) and 2 (Castillo de Mula): (A) *Mf1*, sample 2; (B) *Mf2*, sample 4; (C) *Mf3*, sample 9; (D) *Mf4*, sample 10; (E) *Mf5*, sample 13; (F) *Mf6*, sample 14. (G) *Mf7*, sample 17. (H) *Mf10*, sample 20. Scale bar: samples a-e: 1000 μm ; sample f: 100 μm . Key: a, alveolinid; as, asterigerinid; b, bryozoan; bf, benthic foraminifer; c, coral; cc, crustose coralline algae; da, dasyclade algae; di, discorbid; d, discocyclinid; ef, encrusting foraminifer; g, gastropod; gc, geniculate coralline algae; mi, miliolid; mo, mollusk; pf, planktonic foraminifer; ep, echinoid plate; es, echinoid spine; hef, hyaline encrusting foraminifer; i, intraclast; l, lithoclast; m, miliolid; n, *Nummulites*; or, *Orbitolites*; os, ostracod; pl, planorbulinid; rr, reworked rotaliid; r, rotaliid; so, solenomerid.

Fig. 5. Relative abundance of components recognized in the studied thin sections of the Stratigraphic Sections 1 (Doñana) and 2 (Castillo de Mula).

Fig. 6. Photomicrographs microfacies of the Stratigraphic Sections 3 (Prado Mayor) and 4 (Malvariche): (A) *Mf8*, sample 31; (B) *Mf18*, sample 32; (C) *Mf9*, sample 40; (D) *Mf11*, sample 39; (E) *Mf12*, sample 44; (F) *Mf13*, sample 46. Scale bar: 1000 μm . Key: a, alveolinid; as, asterigerinid; b, bryozoan; bf, benthic foraminifer; c, coral; cc, crustose coralline algae; da, dasyclade algae; d, discocyclinid; ep, echinoid plate; es, echinoid spine; hef, hyaline encrusting foraminifer; i, intraclast; g, gastropod; l, lithoclast; m, miliolid; n, *Nummulites*; or, *Orbitolites*; os, ostracod; pl, planorbulinid; rr, reworked rotaliid; so, solenomerid.

Fig. 7. Relative abundance of components recognized in the studied thin sections of the Stratigraphic Sections 3 (Prado Mayor) and 4 (Malvariche).

Fig. 8. Environmental distribution of microfacies of the Paleocene marine Depositional Sequence 1 (Mula-Doñana Fms.) in Sierra Espuña. Arranged from proximal to distal depositional environments: *Mf1*, Restricted inner ramp supratidal-intertidal environment ; *Mf2*, Protected lagoon environment ; *Mf3*, Shoal or channel deposits near reef and rodophyta maërl environment ; *Mf4*, Reef and rodophyta maërl environment; the upper image corresponds to the back-reef environment while the lower image corresponds to the maërl environment ; *Mf5*, Middle ramp slope environment; *Mf6*, Outer ramp environment. Key: fwwb (fair weather wave base); swb (storm wave base).

Fig. 9. Environmental microfacies distribution for the lower Eocene marine Depositional Sequence 2 (Espuña-Valdelaparra fms) in Sierra Espuña. Arranged from proximal to distal depositional environments: *Mf13*, Inner ramp lagoon, upper subtidal environment; *Mf12*, Inner ramp shoal, upper subtidal environment; *Mf11*, Distal inner ramp seagrass environment; *Mf8*, Middle ramp maërl environment; *Mf7-9*, Distal middle ramp maërl (uppermost image) and middle ramp hyaline LBF (Larger Benthic Foraminifera) accumulations (nummulitids) (lowermost image); *Mf10*, Middle ramp LBF accumulations (flat nummulitids and orthophragminids) in a distal middle ramp environment. Key: fwwb (fair weather wave base); swb (storm wave base).

Fig. 10. Paleogeographic and peleoenvironmental sketch maps of the Mula Basin-Sierra Espuña area. (A) Paleocene. (B) Early Eocene.

Fig. 11. (A) Paleogeographic sketch map near the Cretaceous/Cenozoic boundary (about 70 Ma) showing the location of the study area and the compared sectors (after Scheibner and Speijer, 2008; Martín-Martín et al., 2019b; modified). (B) Biochronostratigraphy of the Malaguide units and biogenic assemblage (corals and LBF) of the Paleocene-early Eocene coming from the Sierra Espuña-Mula Basins, and comparison with similar characters of the Prebetic Units (Spain) and temperate Circum-Tethyan Platform Stages (Scheibner and Speijer, 2008; Höntzsch et al., 2013).

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Table 1. Lithostratigraphic data of the studied stratigraphic sections with the representation of the interval thickness, name of formation, samples collected, age, fossils visible to naked eyes and lithofacies description (Martín-Martín, 1996; Martín-Martín et al., 1997a, 1997b; Serra-Kiel et al., 1998a).

LITHOSTRATIGRAPHIC DATA OF THE STUDIED SECTIONS (LOGS)				
Morrón de Totana Unit (Maláguide Domain, Internal Betic Zone)				
Lithostratigraphic Section (Log 1) – Locality: Doñana (Mula Basin)				
Thickness (m)	Formation	Samples	Age	Field litho-biofacies description
5	MULA	10	Upper Paleocene (Selandian)	P2 interval: massive biocalcarenes beds with prevalently; cross lamination (laminae 0,5 cm); occasional up to 1 cm thick calcareous clasts; grain size: medium to coarse sand; only the basal bed (1 m thick) is stratified; presence of algae
		8, 9		
30	(65 m)	5, 6, 7	Lower Paleocene (Danian)	P1 interval: poorly stratified marly-calcarene succession. The lowest 30 m constitute a para-sequence showing an increase in number and thickness of the calcarenite beds that show lamination at the top of the layers; fine to coarse grain size; presence of Miliolides, benthic foraminifera and <i>Solenomeris</i>
		3, 4		
30		1, 2, 3		
	Tectonic contact		Thrust	
>30	RIO PLIEGO	---	Ciudad Granada Group (Malaguide), overturned in Log 2; brownish turbidite succession	
Lithostratigraphic Section (Log 2) – Locality: Castillo de Mula (Mula Basin)				
Thick (m)	Formation	Samples	Age	Field litho-biofacies description
10	ESPUÑA	20	Lower Eocene (Ypresian)	F2 interval: amalgamated biocalcarenes: normally non-stratified laterally variable in thickness lenticular bodies; grain size coarser and fossils dimensions up to 1-2 cm; algae rarer than Log 1.
		18, 19		
4	(14 m)	17	Cuisian	F1 interval: amalgamated biocalcarenes: poorly stratified, fine to medium grained, with algae (rodholites) sometimes with dimensions up to some cm and <i>Nummulites</i>
		16		
	Erosion surface		Ilerdian <i>p.p.</i> Stratigraphic gap (Ilerdian <i>p.p.</i> = Early Ypresian= Thanetian); missing interval everywhere (Thanetian <i>p.p.</i>)	
40	MULA	15 13,14	Upper Paleocene (Thanetian)	P3 interval: Poorly stratified calcarenites, biocalcarenes and arenites; variable grain size (from more frequent fine sand to coarse sand); occasional interlayers of silt-sandy marls; bed thickness ranges laterally and vertically between 10-20 cm and 1m; presence of algae

11,12

and miliolids

Lithostratigraphic Section (Log 3) – Locality: Prado Mayor (Sierra Espuña)

Thick (m)	Formation	Samples	Age	Field litho-biofacies description
30	VALDELAPAR	47, 48	Lower Eocene	H3 interval: as H1 , but pelites/arenites+limestones ratio =70/30; freshwater gastropods rich limestones (transitional environment)
		45, 46		
40	RA (73 m)	---	(Ypresian) Latest Cuisian	H1 interval: (partially-covered): homogeneous yellowish-gray silty-sandy mudstones with occasional decimetric beds of arenites (quartz, muscovite, lithic fragments, etc.), calcareous cement (pelites/arenites + limestones ratio = 95/5)
3	ESPUÑA (18 m)	44	Lower Eocene (Ypresian) Lower-Middle Cuisian	G interval: amalgamated blackish-gray and brownish micritic limestones with abundant miliolids, occasional alveolinids and <i>Orbitolites</i> (very restricted environment as an estuary)
3		43		A2: metric biomicritic limestones with very abundant alveolinids; frequent <i>Nummulites</i> , <i>Assilina</i> and operculiniform <i>Assilina</i>
3		42		A4a interval: as A4, but but with up to 20-30 cm frondescent corals
3		41		A4 interval: decimetric micritic limestones characterized by poor fossil content; in the upper part, up to 20-30 cm large frondescent corals (litho-biofacies A4a) are frequent
4		40		A3 interval: fine biocalcarenes with very abundant <i>Nummulites</i> and very rare alveolinids
3		39		A2 interval: metric biomicritic limestones with very abundant Alveolinae; frequent <i>Nummulites</i> , <i>Assilina</i> , operculiniform <i>Assilina</i> (less abundant than <i>Assilina</i>)
2		38		A1 interval: pluri-decametric limestones with micro-conglomerate bands containing quartzitic clasts (size from mm to cm) and less frequent alveolinids
		<i>Angular unconformity</i>		
>30	CAPAS BLANCAS		Upper Cretaceous	Gray-whitish stratified marls, calcareous marls, marly limestones and limestones with frequent grayish and blackish chert lens and levels; presence of tubes of <i>Belemnites</i>

Lithostratigraphic Section (Log 4) – Locality: Malvariche (Sierra Espuña)

Thick (m)	Formation	Samples	Age	Field litho-biofacies description
25	VALDELAPARRA	36, 37 34, 35 32, 33	Lower Eocene (Ypresian) Uppermost Cuisian	G interval: amalgamated blackish-gray and brownish micritic limestones with abundant miliolids, occasional alveolinids and <i>Orbitolites</i> (probably very restricted environment as an estuary)

7	31		E interval: see description below
3	30		F interval: see description below
7	29	Lower Eocene	E interval: see description below
6	28	(Ypresian)	F interval: See description below
9	27	Middle-Upper Cuisian	E interval: see description below
3	25, 26		F interval: as litho-biofacies E , but here decimetric and stratified beds and with <i>Nummulites</i> much more abundant than alveolinids (most external carbonate platform)
		ESPUÑA	
		(55 m)	
8	24	Lower Eocene	E interval: metric, stratified detritic limestones (fine to medium grain size) with up to 0,3 cm large Qz and sometimes chert clasts; abundant alveolinids and less frequent <i>Nummulites</i> ; pockets and bands very rich in coarser fossils and with scarce matrix; sometimes with <i>Solenomeris</i> (encrusting benthic foraminifera)
6,7	23	(Ypresian) Lower Cuisian	D interval: the succession is poorly stratified; the lithofacies are occasionally plane-parallel laminated and often the the base is consists of conglomeratic (clasts up to 4-8 cm) bio-calcarenes with rounded quartz pebbles and very abundant <i>Nummulites</i> , alveolinids and echinoderms (without algae) often concentrated inside pocket or in coarser levels (fine to coarse grain size)
0,3	---		B interval: lagoon environment

Table 2. *Mf1* to *Mf13* description with the relative abundance of components, and depositional environment interpretation. Studied samples and fossil content (common, abundant, present and/or rare) are also exposed.

Microfacies	Stratigraphic Section, samples and corresponding lithofacies	Fossils and other common or abundant* components	Fossils and other presents or rare components	Reconstructed depositional environment
<i>Mf1</i> Quartzsiltite to quartzarenite with gastropods	Doñana Section 1-3 P1	Dasycladales; discorbids and other hyaline small benthic foraminifera; small gastropods; ostracods; dasyclade algal remains	Rotaliids; textularids; miliolids; planktonic foraminifers; reworked fragments of <i>Microcodium</i> (?) in corn-cob aggregates and disarticulates grains	Restricted inner ramp
<i>Mf2</i> Rhodolith and coral floatstone-packstone	Doñana Section 4-7 P1	Coral pebbles encrusted by coralline algae; debris of crustose and geniculate coralline algae into packstone bioclastic matrix; <i>Idalina</i> and small miliolids*, hyaline small benthic foraminifera (discorbids, rotaliids); lunulitiform and vinculariform colonies of bryozoans; gastropods; echinoid plates and spines; reworked fragments of <i>Microcodium</i>	Quartz, <i>Microcodium</i> ? debris; dasycladales; <i>Ovulites</i> (codiacean?); <i>Solenomeris</i> ; agglutinated haddonids, bolivinids; textularids; ostracods; annelids;	Protected inner ramp - lagoon
<i>Mf3</i> Coral and red algae grainstone-packstone	Doñana Section 8, 9 P2	Pebbles and grains* of rounded coral and <i>Solenomeris</i> fragments, non-geniculate coralline algae (<i>Sporolithon</i>) and intraclasts. Scattered geniculate corallinales, <i>Idalina</i> and small miliolids*, rotaliids,	<i>Glomalveolina</i> , <i>Elphidium</i> , reworked and coated rotaliid grains, valvulinids, haddonids; dasycladales; gastropods, bivalves; annelids	Shoal or channel deposits near reefs and rodophyta crust

			miscellanids*, discorbids; bryozoans; echinoid plates and spines		
Mf4	Doñana Section		Warty to fruticose crustose coralline red algae; <i>Solenomeris</i> * macroids and coral pebbles encrusted by crustose coralline algae; intraclasts, lithoclasts; crustose and geniculate coralline algal debris; peysonelliacean red algae (<i>Polystrata alba</i>); miliolids*, miscellanids; codiacean green algae; membraniporiform and adeoniform bryozoan colonies; echinoid plates and spines	Rotaliids, textularids, haddonids; dasycladales; bivalves; annelids	Lagoonal back-reef and rodophyta crust (Maërl) in inner to middle ramp
Crustose coralline algae and <i>Solenomeris</i> bindstone	10 P2				
Mf5	Castillo de Mula Section		Coral and <i>Solenomeris</i> pebbles*; crustose and geniculate coralline debris*; coated discorbids, miliolids, miscellanids, textularids; lunulitiform and adeoniform bryozoan colonies; echinoid plates and spines	Dasycladales; solenoporaceans (<i>Elianella elegans</i>), rotaliids, haddonids; mollusc fragments	Reef slope deposits in a mesophotic middle ramp
Coral and <i>Solenomeris</i> floatstone- packstone	11-13 P3				
Mf6	Castillo de Mula Section		Discorbids, planktonic foraminifers, textularids; ostracods; bryozoans; echinoid plates; aggregate grains	Dasycladales; rotaliids; mollusc fragments	Outer ramp
Quartzarenitic wackestone with planktonic foraminifers	14-15 P3				
Mf7	Castillo de Mula Section		Rhodoliths (<i>Sporolithon</i>)*; <i>Solenomeris</i> macroids*; crustose coralline algae*; acervulinids (<i>Acervulina</i>), rotaliids, <i>Nummulites</i> *	<i>Distichoplax biserialis</i> ; operculiniform <i>Assilina</i> , <i>Amphistegina</i> , <i>Sphaerogypsina</i> , <i>Planorbulina</i> , bolivinids, planktonic foraminifers; miliolids, textularids, valvulinids, haddonids;	Middle ramp hyaline LBF accumulations to middle ramp maërl Mesophotic environment
Rhodolith, nummulitid and orthophragminid floatstone	16-17 F1				

		<i>Discocyclus</i> *, <i>Asterocyclus</i> *; geniculate and crustose coralline algae debris; vinculariform bryozoans; echinoid plates and spines; pellets*; coated grains*	ostracods; annelids	
Mf8	Castillo de Mula, Prado Mayor and Malvariche Sections 18, 29-32, 41-42 F1, A2 to A4, E+F, F, G	Rhodoliths (<i>Sporolithon</i>); <i>Solenomeris</i> macroids wrapped by crustose coralline algae (<i>Lithoporella</i>) and hyaline encrusting foraminifers (<i>Acervulina</i> , <i>Miniacina</i>); miliolids, rotaliids; <i>Distichoplax</i> <i>biserialis</i> *; bryozoans*; molluscs (gastropods and pelecypods); coral- bryozoan and intraclast pebbles; crustose coralline algal debris; echinoid plates and spines; pellets*	<i>Nummulites</i> , <i>Alveolina</i> , textularids, valvulinids, planorbulinids, and rounded reworked grains of <i>Glomalveolina</i> and rotaliids; dasycladal and codiacean green algae; crustose and geniculate coralline algal fragments	Proximal middle ramp coral-maërl Mesophotic environment
Mf9	Castillo de Mula, Prado Mayor and Malvariche Sections 19, 25-28, 40 F2, A1, E+F	<i>Nummulites</i> *; <i>Assilina</i> , operculiniform <i>Assilina</i> , <i>Amphistegina</i> , <i>Asterigerina</i> , rotaliids; crustose coralline and mollusc fragments; echinoid plates	<i>Glomalveolina</i> , miliolids, discorbids, textularids	Middle ramp hyaline LBF accumulations Mesophotic environment
Mf10	Castillo de Mula Section 20 F2	<i>Nummulites</i> *, <i>Discocyclus</i> *, <i>Assilina</i> *, operculiniform <i>Assilina</i> ; solitary corals; turruculate gastropods, pelecypods; echinoid spines; annelids, glauconite	Miliolids, bolivinids, textularids, valvulinids, planktonic foraminifers; ostracods	Middle ramp hyaline LBF accumulations Mesophotic to oligo-photoc environment
Mf11	Prado Mayor and Malvariche Sections	<i>Alveolina</i> *, <i>Orbitolites</i> *, <i>Nummulites</i> ,	Dasycladales; crustose coralline algal fragments; <i>Distichoplax</i>	Inner ramp sea- grass Euphotic lower

packstone	33, 38, 39 21-24, A1, A D, G	operculiniform <i>Assilina</i> , <i>Amphistegina</i> , miliolids*, rotaliids, discorbids*, textularids; echinoid plates and spines	<i>biserialis</i> ; annelids; quartz grains	subtidal
Mf12 Alveolinid and <i>Nummulites</i> packstone- grainstone	Prado Mayor and Malvariche Sections 34-35, 43, 44 A4, G	Rounded grains of <i>Alveolina</i> *, <i>Glomalveolina</i> *, <i>Nummulites</i> *, miliolids, rotaliids, discorbids, textularids; <i>Solenomeris</i> ; crustose and geniculate coralline algae, <i>Distichoplax</i> <i>biserialis</i> ; dasycladales; gastropods; echinoid plates; pellets*	Operculiniform <i>Assilina</i> ; rounded lithoclasts	Inner ramp shoal Euphotic upper subtidal
Mf13 Gastropod and ostracod calcsiltitic wackestone	Prado Mayor and Malvariche Sections 22, 36-37, 45- 48 H3, B+C, G	Gastropods; ostracods*; textularids; pellets*	Glauconite	Inner ramp lagoon Euphotic upper subtidal

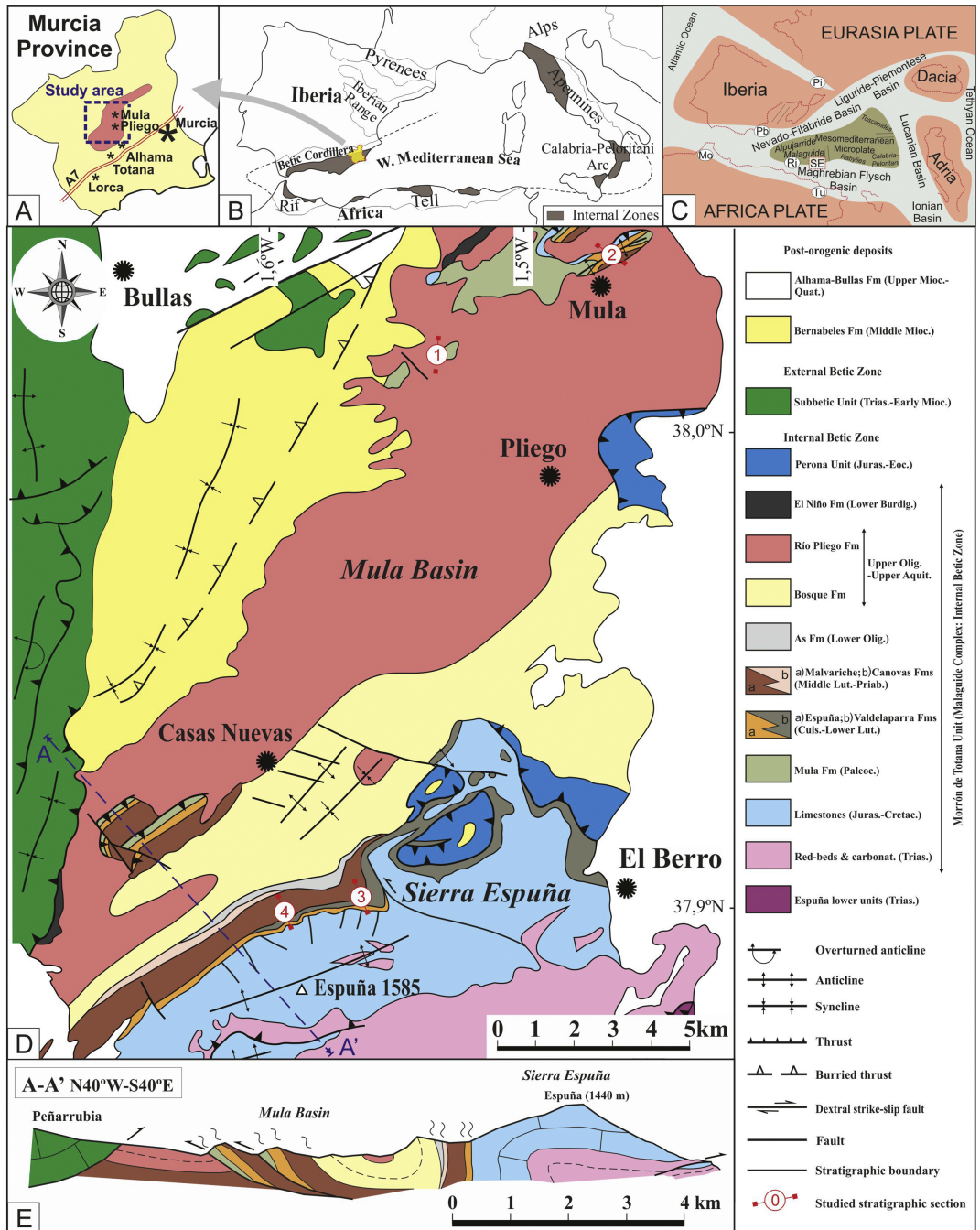
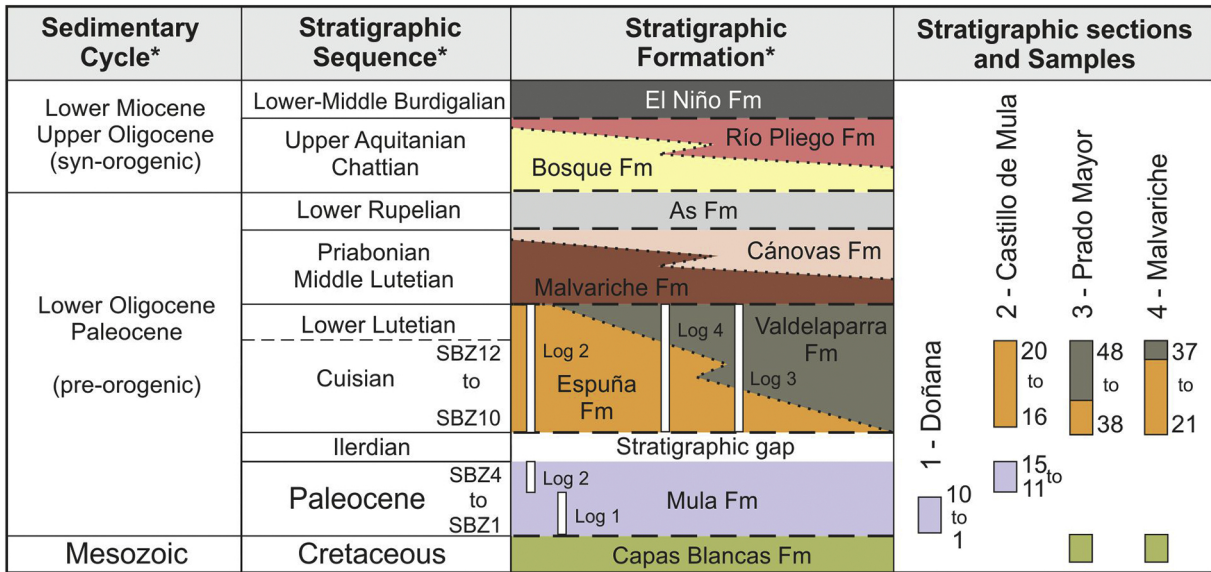


Figure 1

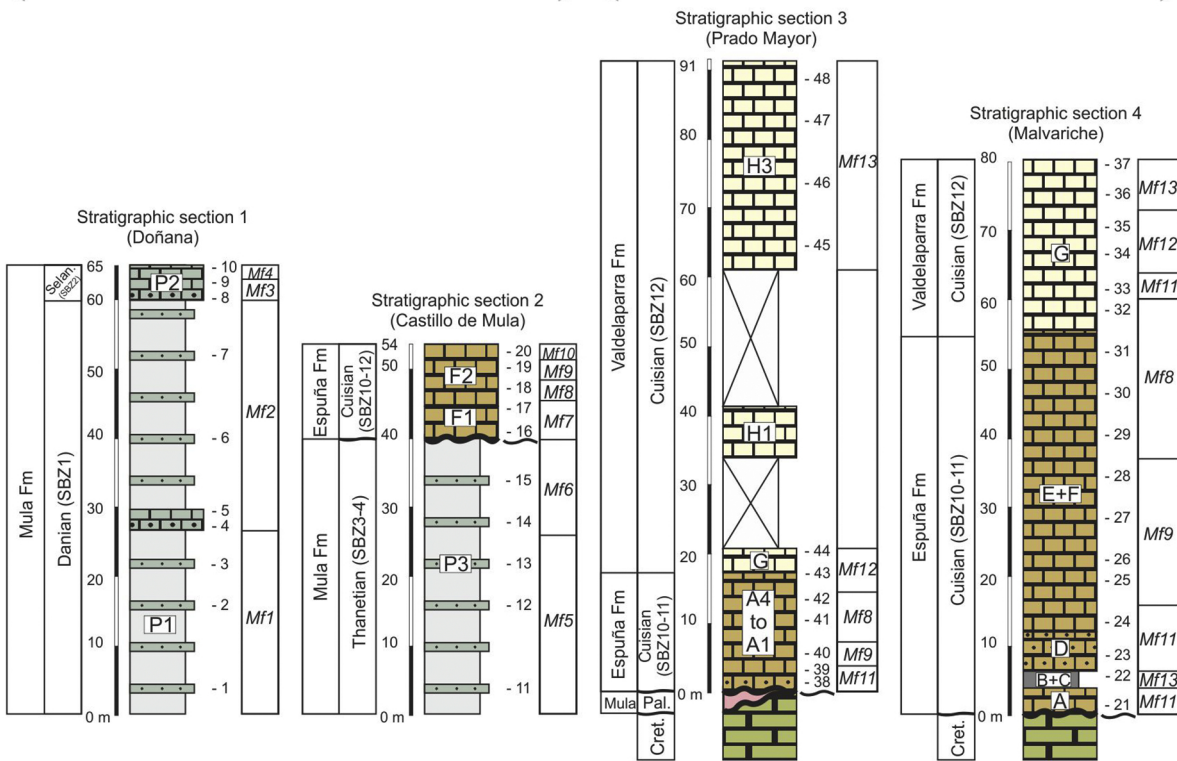


* According to Martín-Martín (1996) and Martín-Martín et al. (1997a,b);
SBZ = Shallow Benthic Zone (according to Serra-Kiel et al., 1998 a,b)

Figure 2

Mula Basin

Sierra Espuña



- Massive limestones and calcarenites (Paleocene)
- Calcareous conglomerates (Paleocene)
- Marls with calcarenite intercalations (Paleocene)
- Garumian-like facies with microcodium (Paleocene)
- Marls and calcareous marls (Upper Cretaceous)
- Unconformity

Mula Fm

- Micritic limestones with gastropods (Cuisian)
- Sandy calcarenites with quartz pebbles (Cuisian)
- Marly pelites (Cuisian)
- Amalgamated calcarenites with larger foraminifera (Cuisian)
- Lithofacies (see Table 1)
- Semicovered

Valdelaparra Fm
Espuña Fm

Figure 3

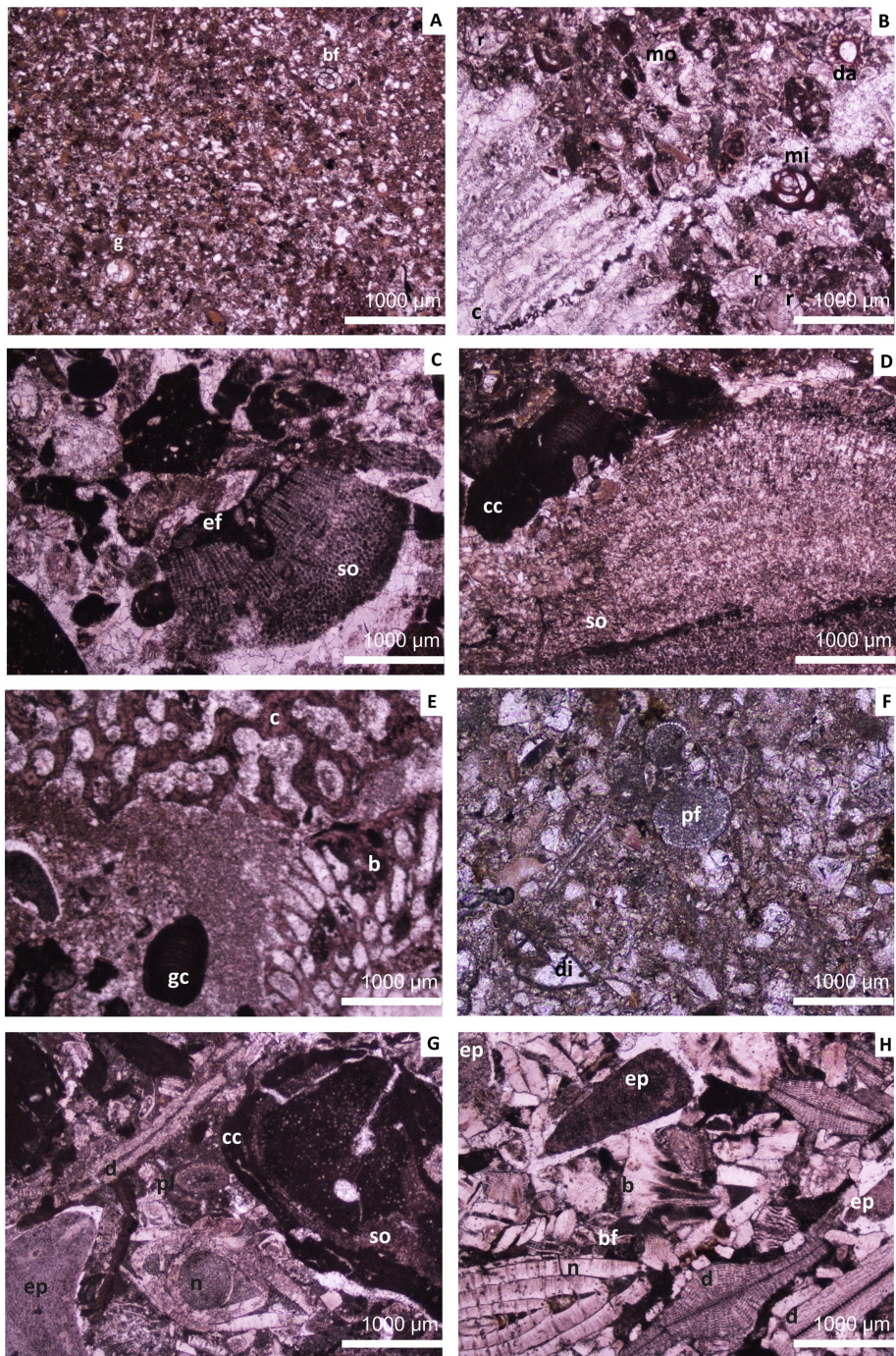


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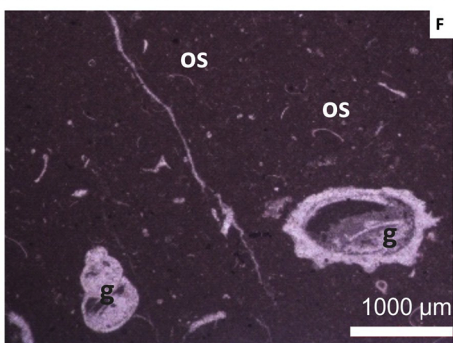
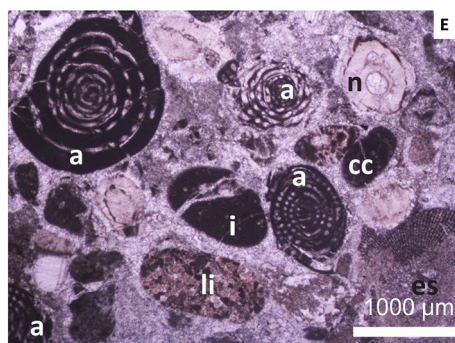
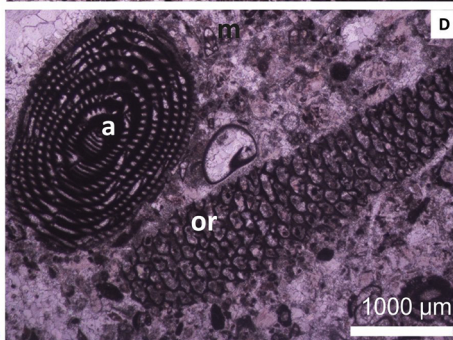
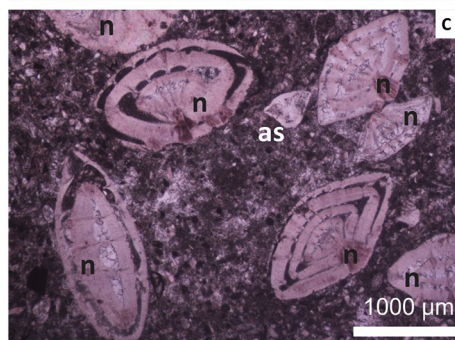
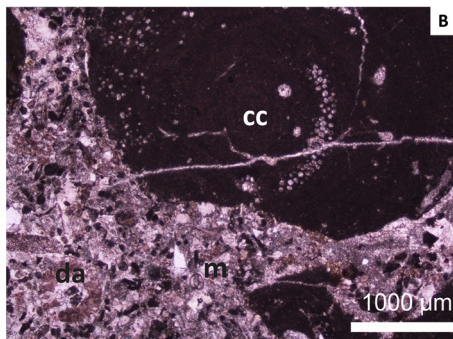
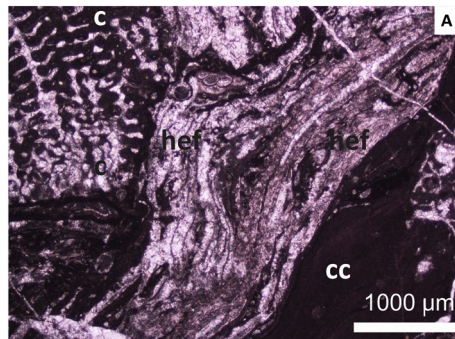


Figure 6

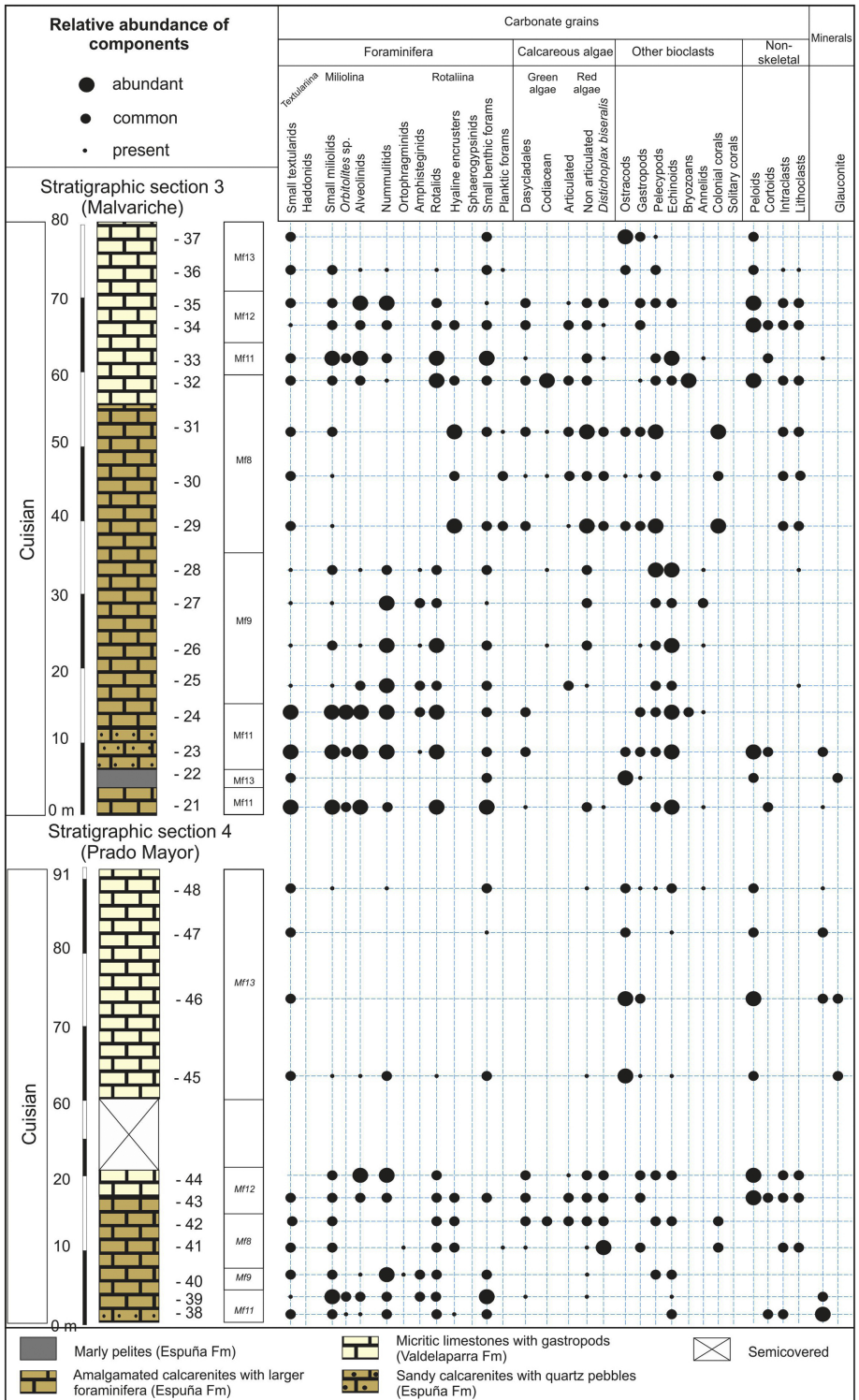


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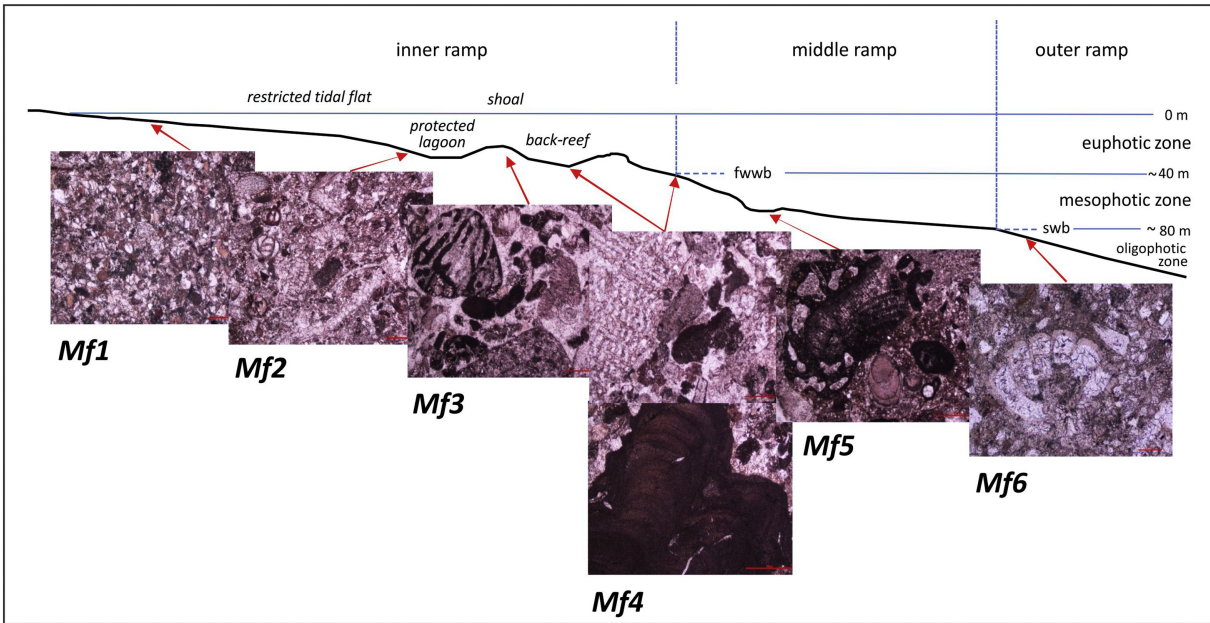


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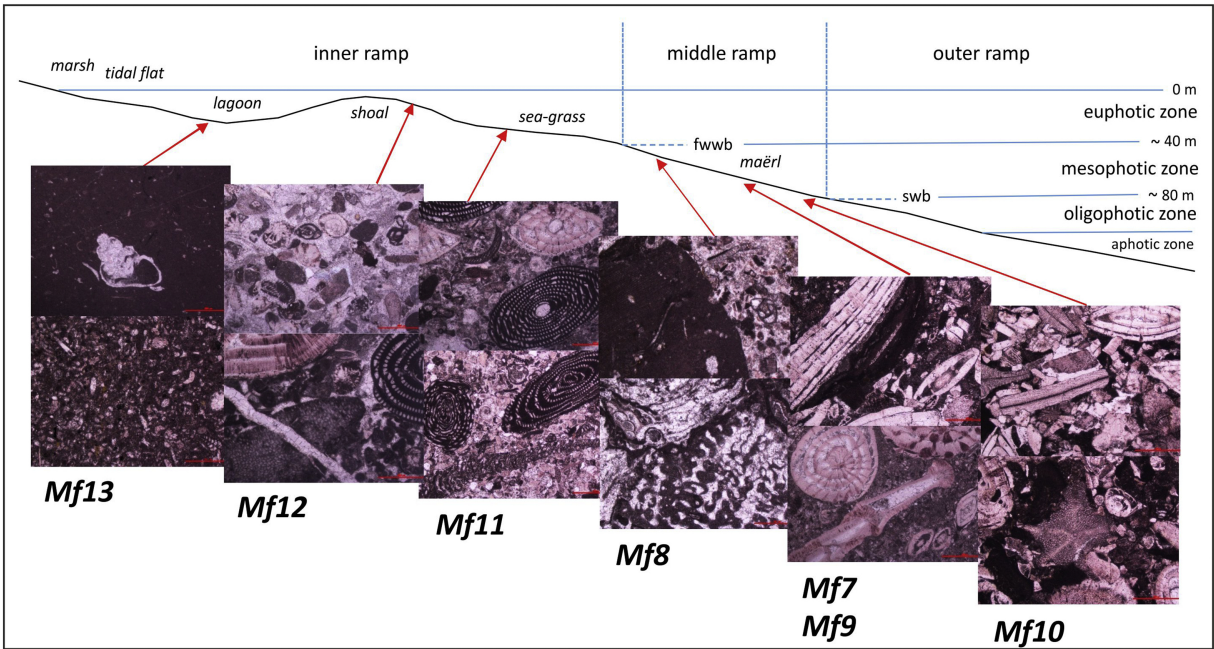
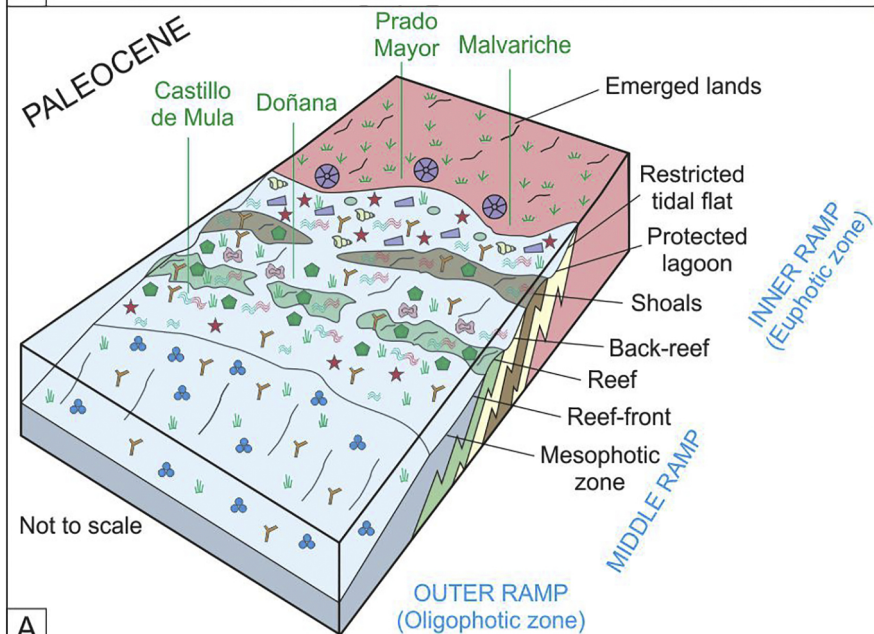
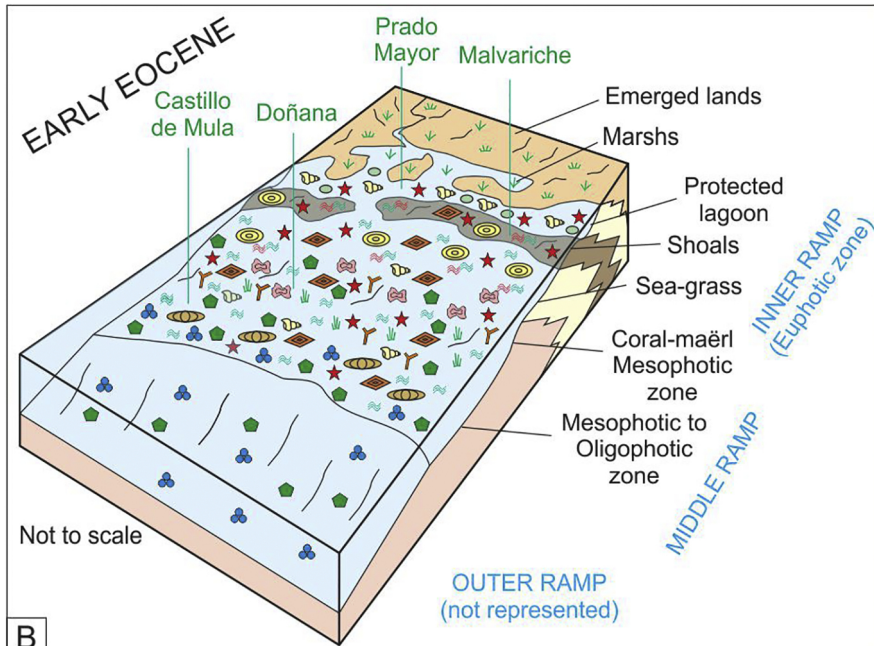


Figure 9



- | | | | | | |
|--|----------------------------|--|--------------------------|--|----------------------------|
| | Disarticulated Microcodium | | Coralline algae | | Alveolines |
| | Articulated Microcodium | | Green algae | | Nummulites |
| | Gastropods | | Rhodoliths and red algae | | Flat larger foraminifera |
| | Ostracods | | Corals | | Small benthic foraminifers |
| | Solenomeris sp | | Bryozoans | | Planktonic foraminifers |

Figure 10

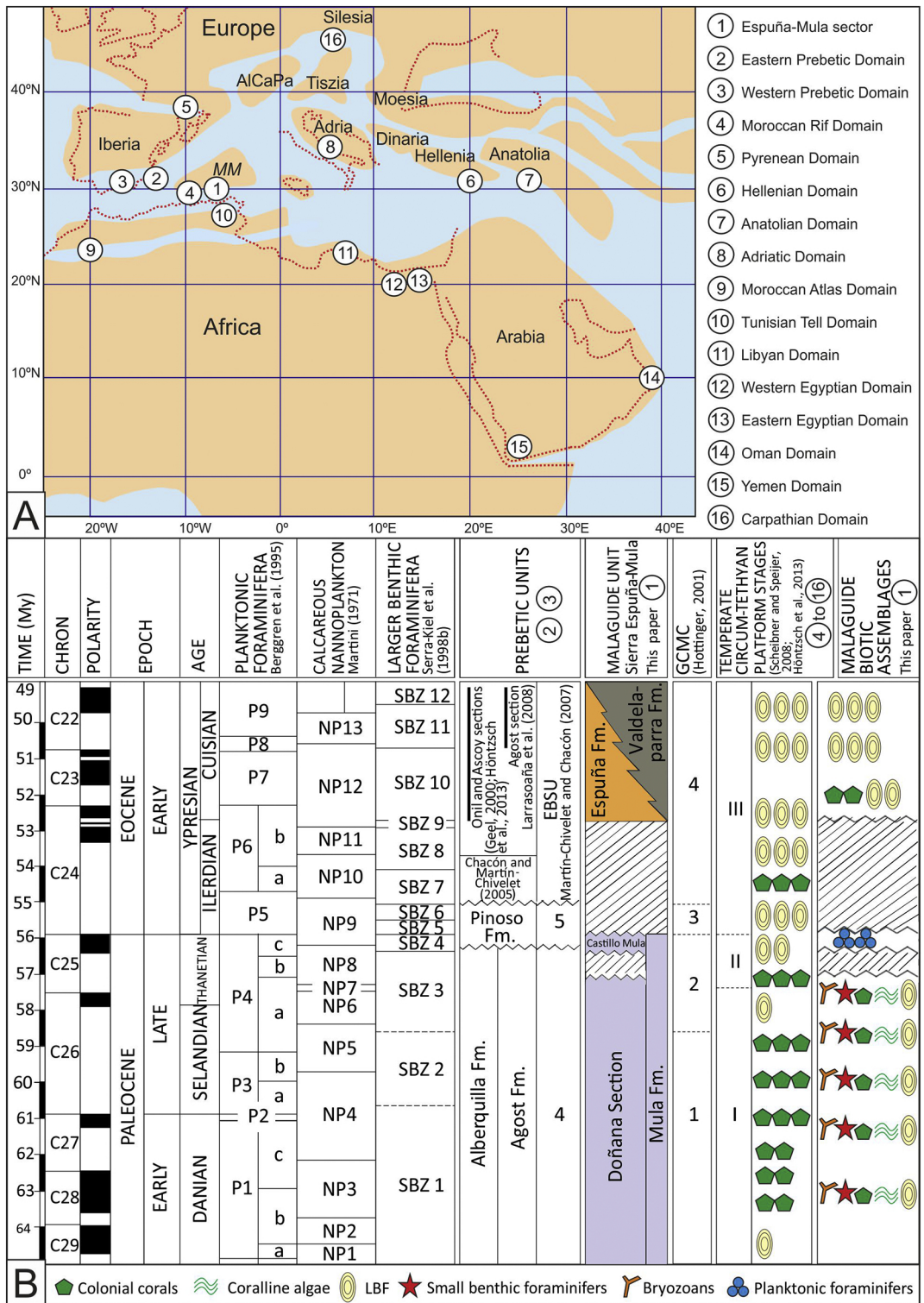


Figure 11