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Paleocene-Eocene evolution of the Prebetics (South Iberian Margin, South Spain) and comparison with other western Tethyan margins

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ABSTRACT

Thirteen Paleocene-Eocene sections have been studied along the Prebetic Domain (South Iberian Margin) in the Alicante, Murcia, Granada, and Jaen Sectors. The sedimentary realms (mostly consisting in 15 shallow marine Lithofacies) and the tectono-sedimentary evolution were characterized. Three informal stratigraphic formations were proposed and dated with planktic foraminifera, calcareous nannoplankton, and Larger Benthic Foraminifera (LBF): (1) lower marly-clayey fm; (2) intermediate limestone-calcarenite fm; and (3) upper marly-clayey fm. The stratigraphic architecture shows diachronous boundaries and lateral passages, representing the internal and external platform (upper slope in a few cases). The lower marly-clayey fm is upper Paleocene to middle Lutetian, the intermediate limestone-calcarenite fm ranges from lower Ypresian to lower Bartonian, while the upper marly-clayey formation is lower Lutetian to lower Priabonian. The diachronism can be due to the inherent sedimentary paleoenvironment changes and to climatic-tectonic interferences. The noticeable thickness variations of sedimentary successions in the studied sections could indicate a synsedimentary tectonics with upward and downward movements of blocks or folds. During the Paleocene-Eocene, the studied area was part of the meridional belt of platforms in the western Tethys. A comparison with other sectors of the central-western Mediterranean area has been performed to evidence synchronous events at Tethyan scale. The compared margins experienced a common pre-foredeep evolution affected by the Eo-Alpine tectonics (Cretaceous to Paleogene) contemporaneously to the establishment of shallow and deep palaeoecological realms. In the case of shallow sedimentary successions, LBF and corals are registered. Comparable gaps in sedimentation are recorded in most of the correlated domains.

1. Introduction

The Paleocene-Eocene was a time-span of changing climate with several main hyperthermal events widely documented (e.g. Dickens et al., 1977; Kennett and Stott, 1991; Zachos et al., 2001; Bohaty et al., 2009; Rivero-Cuesta et al., 2020). The most mentioned events for their consequences on life are: (1) the Paleocene-Eocene transition Thermal Maximum (55.5 Ma) (e.g. Kennett and Stott, 1991; Koch et al., 1992; Thomas and Shackleton, 1996); (2) the Early Eocene Climatic Optimum (53-50 Ma) (e.g. Zachos et al., 2001, 2008); and (3) the Middle Eocene Climatic Optimum (41-40 Ma) (e.g. Bohaty and Zachos, 2003; Zachos et al., 2008). In general terms, these hyperthermal events drove to major oceanographic, environmental, and atmospheric changes, as mentioned by Kennett and Stott (1991), Koch et al. (1992), Zachos et al. (1993), Thomas and Shackleton (1996), Zachos et al. (2001), and Pujalte et al. (2003), among others.

One of the main changes was the development of carbonate ramps (rich in larger benthic foraminifera and zooxanthellate corals) mainly located in two belts on the margins of the Tethys Ocean. On the northern edge, a carbonate belt developed at latitudes of about 40°N

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(Martín-Martín et al., 2020c, 2021, 2023b, 2024; Tosquella et al., 2022), stretching from the Pyrenean realm to the Caucasus region, including the Alpine, Carpathian, Helenian, and Anatolian platforms (Scheibner and Speijer, 2008; Pomar et al., 2017; Müller et al., 2019). The other carbonate belt stretched on the southern Tethyan margin, mostly around or below 30°N, being recognized in South Iberian Margin (Prebetics), Malaguide-Ghomaride Domain (Internal Betic-Rif Zone, S Spain and N Morocco), External Zones of North African countries, from Morocco to Egypt, and in the Middle East, as well as Sicily and Adriatic margins from a north African paleogeographic origin (e.g. Scheibner and Speijer, 2008; Höntzsch et al., 2013; Pomar et al., 2017; Müller et al., 2019; Martín-Martín et al., 2020c, 2021, 2023b; Tosquella et al., 2022). The development of these carbonate platforms due to climatic change was coeval with a rising tectonics consequent with the Tethys ocean closing that led to the birth of the Alpine Mountain Chains. The interaction of climatic-tectonic controls must have been recorded in the sedimentation of carbonate platforms since these shallow marine environments are very sensitive to climatic and depth changes (e.g. Tosquella et al., 2022; Martín-Martín et al., 2024).

This paper presents an integrated multidisciplinary analysis of the shallow marine Paleocene-Eocene sedimentary succession to decipher the interaction between climate and tectonic controls in the Prebetic domain (South Iberian Margin). Several other authors worked in the area being their objective rather of local interest (e.g. Dabrio, 1972; Álvarez-Suárez and Dabrio, 1974; Geel et al., 1998; Geel, 2000; Guerrera et al., 2006; Martín-Chivelet and Chacón, 2007; Pujalte et al., 2010; Guerrera and Martín-Martín, 2014a; Guerrera et al., 2014). The present paper, although includes a couple of previously studied sections, propose many new ones, all being studied in a regional context. These deposits are widespread along the chain, both in the Internal and External Prebetics, from Alicante (to the east) to Granada (to the west), passing through the Murcia and Jaen provinces (Fig. 1B). A better stratigraphic framework was built for this shallow marine and/or continental sedimentary succession despite the scarcity of relevant fossil content. To maximize the chances of dating success, a biostratigraphic analysis of planktonic foraminifera, calcareous nannoplankton, and Larger Benthic Foraminifera (LBF) was performed in this study. The results were used to reconstruct the Paleocene-Eocene stratigraphic architecture of the Prebetics in order to achieve the vertical and lateral evolution model of the sedimentary realms. A thickness analysis has been performed to obtain certain information about relative tectonic movements (sinking and rising areas). Finally, palaeogeographic-palaecological constraints has been obtained and correlated with the general Paleocene-Eocene framework of the Central-Western Mediterranean area by using a GPlates basemap according to the reconstructions proposed by Müller et al. (2018, 2019) and Le Breton et al. (2021).

2. Geological framework

The Betic Cordillera is the westernmost Alpine European mountain chain (Fig. 1A) and is classically divided into Internal and External Zones, and the Maghrebian Flysch Basin Units in between (Vera, 2004; Martín-Martín et al., 2020a, 2020b) (Fig. 1B). The External Betic Zone, the topic of this work, is divided into two main tectono-paleogeographic domains derived from the South Iberian Margin (Fig. 1B): i) the shallow marine Prebetic, stratigraphically continuous with the northern foreland (Iberian Meseta); and ii) the unrooted pelagic Subbetic (southward from the Prebetic). Both domains are also subdivided in several sub-domains. The Prebetic is divided, from north to south, in the shallower External Prebetic and the relatively deeper Internal Prebetic. The Subbetic (always deeper than the Prebetic) is divided, from north to south, into the shallow External, deep Middle, and the relatively shallow Internal Subbetics. In all cases these domains consist of Triassic to Cenozoic sedimentary successions progressively structured, from south to north, during the Middle-Late Miocene as a pile of nappes (Vera, 2000; Arias et al., 2004). Up to now, the studies in the Cenozoic from the Prebetics

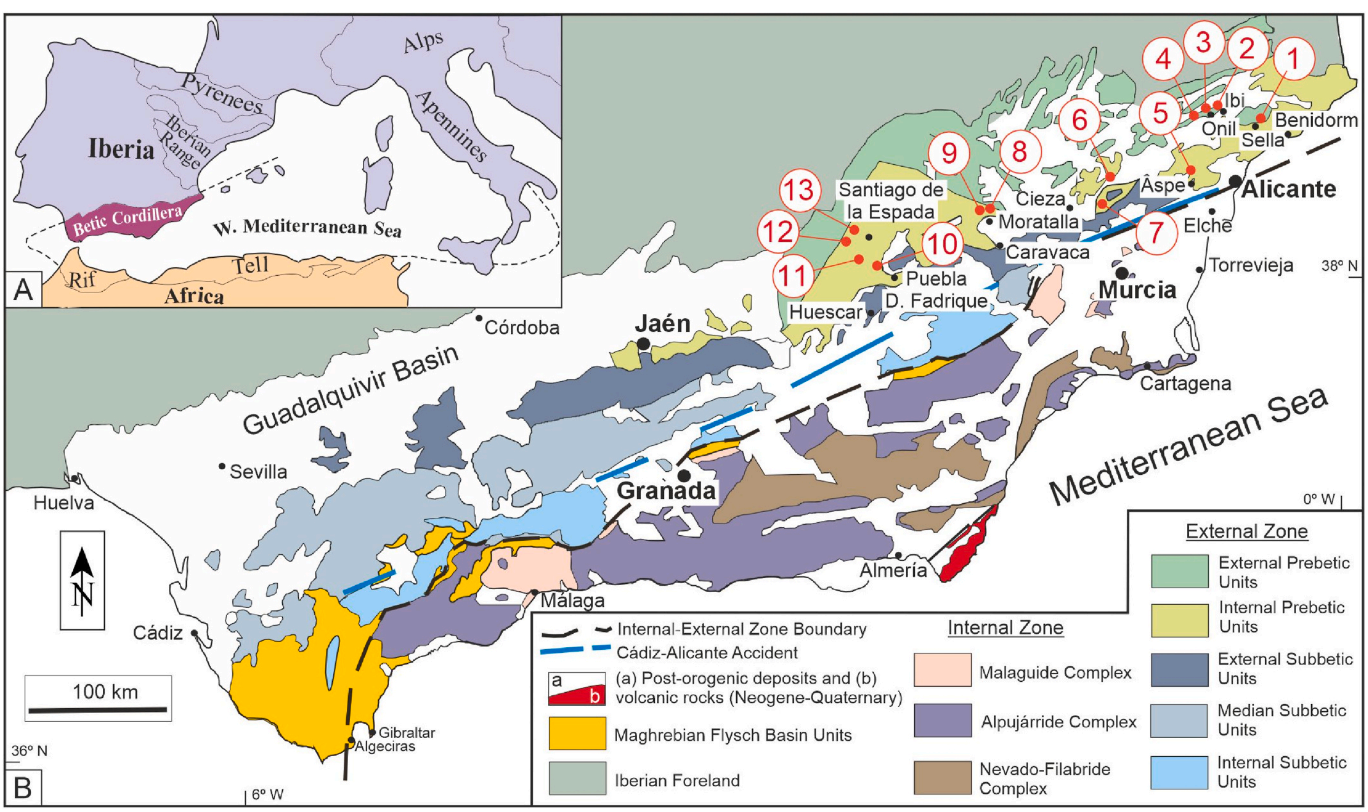

Fig. 1. Simplified geological map of the Betic Cordillera (redrawn after Vera, 2004). (A) Alpine Chain map of the western-central Mediterranean area; (B) geological map of the Betic Cordillera, showing the locations of the thirteen measured and reconstructed stratigraphic successions.

have been performed locally in determinate areas and it is still needed an integrating study of the entire tectono-paleogeographic domain. Several authors (Vera, 2000; Tent-Manclus, 2003; Martin-Rojas et al., 2015; Martín-Martín et al., 2018a, 2018b; Guerrera and Martín-Martín, 2014a; Guerrera et al., 2006, 2014) show that the Prebetic is characterized by a number of strike-slip fault families Cadiz-Alicante Accident system (N70E oriented), Vinalopó Fault system (N155E oriented), and Socovos Fault system (N120E oriented). The fault traces are usually associated with outcropping Triassic clays with gypsum, due to hallokinetic phenomena, while the blocks bounded by the faults are characterized mainly by folded Cretaceous to Miocene successions. The fault traces also reveal Cenozoic deposits related to pull-apart or blend-faults basins (Leret-Verdú and Lendínez-González, 1978; De Ruig, 1992), allowing the dating of the activity of the faults not later than the Neogene. The fold axes in the fault bounded blocks are oriented N20E and N70E (e.g. Colodrón and Ruiz, 1980; De Ruig, 1992; Geel, 1995). The folding systems seem to be related to transpressive conditions under a compressive cinematic regional framework. First, the N70E fault systems (Cadiz-Alicante), under a cinematic regime with a near E-W oriented σ1, generated the N20E oriented folding probably during the Middle Miocene; later, the N120-155E fault systems (Vinalopó and Socovos), with a near NW-SE oriented σ1, generated the N70E oriented folding affecting the Upper Miocene deposits. Therefore, the studied Paleocene-Eocene successions currently appear into numerous blocks bounded by mainly dextral faults that moved after their deposition.

In the Alicante area, the Paleocene-Eocene Prebetic deposits were previously studied by several authors (Geel et al., 1998; Geel, 2000; Guerrera et al., 2006; Martín-Chivelet and Chacón, 2007; Guerrera and Martín-Martín, 2014a) who distinguished two different sedimentation areas: one related to a shallow marine nummulite platform to the NW (Geel et al., 1998; Geel, 2000) and a deeper one with turbidite and olistostromic sedimentation affected by active Paleogene tectonics (Guerrera et al., 2006; Guerrera and Martín-Martín, 2014a). For the deeper turbiditic successions, the stratigraphic framework was better defined, its sedimentary record ranging from Paleocene to upper Eocene, Paleocene in many cases being absent (e.g. Guerrera et al., 2006; Martín-Chivelet and Chacón, 2007; Larrasoaña et al., 2008; Guerrera and Martín-Martín, 2014a). In the Murcia area (and also in the adiacent Albacete), modern studies started in the sixties and seventies (Azéma, 1966a, 1966b, 1977; Rodríguez-Estrella, 1977, 1979). According to them, during Cretaceous and Paleocene, deep pelagic deposits (Scaglia-like facies) sedimented. Several authors (Jérez-Mir, 1973; García-Hernandez, 1978; Azéma, 1977; Vera, 2000; Chacón and Martín-Chirivel, 2005; Molina and Nieto, 2008) pointed out that during the Eocene, the sedimentation changed to a mixed nummulite platform, where marly or calcareous intervals alternated with a terrigenous supply. The deformation evolved during the Neogene in several phases (Montenat, 1977; Guerrera et al., 2014): thrusting during the late Burdigalian, normal faulting during the Middle Miocene, and strike-slip faulting and folding during the Late Miocene. The Paleogene stratigraphy of Prebetics was well defined by Guerrera et al. (2014) who distinguished the shallow Eocene nummulite platforms in the anticlines (Miñano Fm) from deeper turbiditic sedimentation areas in the synclines (Pinoso-Rasa Fm). In all cases, the recent studies indicate active Paleogene tectonics during sedimentation (Guerrera et al., 2014) like that proposed previously for the Alicante area. In the Granada-Jaén areas, the Prebetic Paleocene-Eocene was studied as from the seventies (Dabrio, 1972; Álvarez-Suárez and Dabrio, 1974; Pujalte et al., 2010), two sedimentation areas being also defined (Dabrio, 1972; Pujalte et al., 2010): a shallow nummulite platform, corresponding with Cañada Hermosa Fm, to the N or NW, transitioning southward or southeasternward to deeper marine sedimentation (Nablanca Fm). No synsedimentary tectonics is mentioned in these studies.

3. Methods

The methods by which this study was performed comprise: (1) ***Field analyses***, including logging of the most representative stratigraphic successions in the study area (Fig. 2), structural observations, and extensive sampling (Supplementary Material A1); and (2) ***Laboratory analyses*** concerning microfacies, biostratigraphy, and biochronostratigraphy (Fig. 3). Thirteen sections have been studied along the chain (Fig. 2). The sections were logged for characterizing the sedimentary realms. Among them, three belong to External Prebetics, all in Alicante Sector, all the others to Internal Prebetics. The sections were sampled for biostratigraphic and paleoenvironmental studies. The biostratigraphic study followed standard procedures used for planktonic foraminifera, calcareous nannoplankton, and larger benthic foraminifera (Supplementary Materials A2, A3, and A4). For the Paleocene-Eocene biostratigraphy, the following zonations are used: (1) Olsson et al. (1999), Pearson et al. (2006), and Wade et al. (2011) for planktonic foraminifera; (2) Serra-Kiel et al. (1998) and Papazzoni et al. (2017) for Larger Benthic Foraminifera; and (3) Martini (1971) for calcareous nannoplankton. To this, it must be added the cabinet works when the data obtained through above mentioned methods were processed to elaborate the interdisciplinary results and the palaeogeographic and palaeotectonic reconstructions (graphs and maps) as well as to correlate the main tectono-sedimentary events at regional scale.

4. Results

4.1. Stratigraphy

In the 13 logged sections (Figs. 1 and 2; Supplementary Material A1), 15 sedimentary macrofacies belonging to three stratigraphic formations were defined (Figs. 3 and 4). The lithofacies are (Table 1): L1 – Alveolina limestone; L2 – small-size nummulite limestone; L3 – big-size nummulite limestone; L4 – algal limestone; L5 – coral-rich limestone; L6 – miliolid limestone; L7 – micritic limestone (with or without gastropods and bivalves); L8 – marshy clays-marls and limestones; L9 – marine clays-marls (with or without terrigenous turbidites and/or bioclastic turbidites/debrites); L10 – intraformational breccias; L11 – marine sandstones and conglomerates; L12 – turbidites (L12a – terrigenous turbidite; L12b – bioclastic turbidite); L13 – dolostone and dolomitized limestone, L14 – karstic red clays and continental red-beds, L15 – limestones with terrigenous grains and clasts (mostly quartz). The three informal formations are: lower marly-clayey fm (mostly L9 and L12, but also L2 and L4), intermediate limestone-calcarenite fm (mostly L1 to L8, L10-L11, and L13 to L15, but also L9) and upper marly-clayey fm (mostly L9 and L12, but also L4). The detailed descriptions of the 13 logged sections are given in the Supplementary Material A1.

4.1.1. Alicante Sector

In the Alicante Sector, 5 sections, characterizing both External (Logs 1–4) and Internal (Log 5) Prebetics, have been logged (Fig. 3). The sections are discontinuously exposed, with covered intervals varying from meters to tens of meters. Two or three defined formations are represented in each section.

In the External Prebetics, Sella section (Log 1) shows a succession (ca 120 m thick) consisting of three intervals (Fig. 2). In the lower one crops out the uppermost part of the lower marly-clayey fm, consisting of greenish mudstones (L9) and thin beds (<0.5 m) of limestone with small-size nummulites (L2). It is followed by the second interval (80 m) of almost entirely karstified thick bedded limestones of L2 type and some interlayers of L4. The upper interval (ca 40 m), also karstified, consists of massive algal limestone (L4) with LBF. Both of them belong to the intermediate limestone-calcarenite formation.

A thick succession (ca 215 m), belonging to External Prebetics, was logged in Ibi section (Log 2). Two intervals, corresponding to the lower marly-clayey fm and intermediate limestone-calcarenite fm were

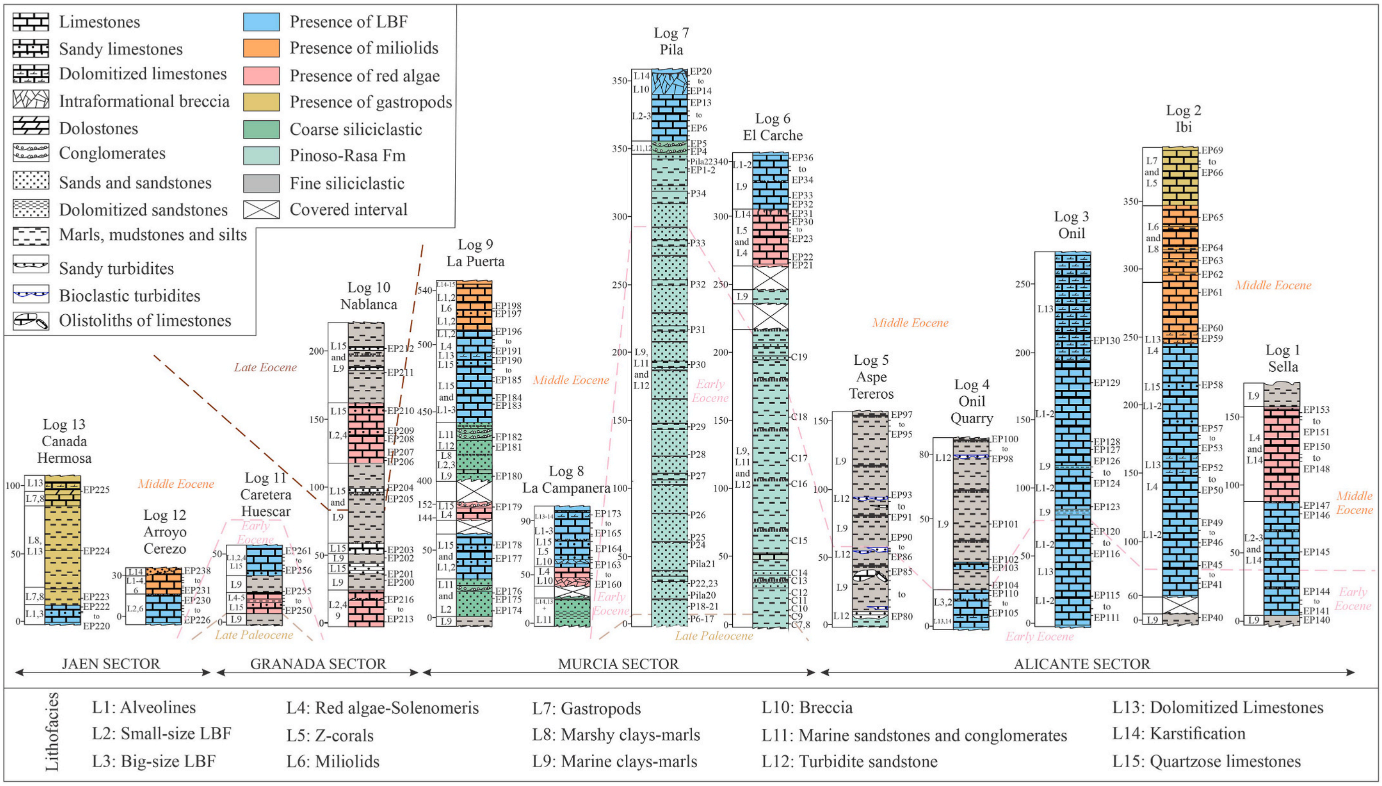

Fig. 2. Paleocene-Eocene new reconstructed stratigraphic successions from the Prebetic domain.

distinguished based on their different sedimentary facies organized in cycles (Fig. 2). The lower interval, which is only poorly exposed, consists in ca 60 m of greenish sandy mudstones (L9) The upper interval (ca 155 m), very rich in LBF, can be subdivided in two subintervals based on the dominant facies, nummulitids vs alveolines. In the lower subinterval (73 m thick), at least 12 cycles of L2-L1 (Fig. 3A and 4B) were defined with L4 infrequently occurring. In the upper subinterval (113 m), cycles of limestones with alveolines (L1) having their tops either with dissolution voids or dolomitizations (L13) are characteristic (Fig. 4H). A terrigenous component in limestones (L15) can be seen toward the subinterval top.

In Onil section (Log 3), the thickest in the area, two main intervals can be recognized, both belonging to the intermediate limestone-calcarenite fm (Fig. 2). The lower one (ca 190 m thick) is dominated by cycles of L1 and L2. Two units of greenish-grey mudstones (L9), 4 and 3 m thick, respectively, divide this interval in three subintervals. L13 occurs from the second subinterval, being more frequent in the third one. The upper interval (>75 m) consists in dolomitized, porous limestones (L13).

Onil Quarry section (Log 3; ca 82 m) consists of an interval of karstified and dolomitized limestone (L14 and L13; Fig. 4G) and massive white limestone (L3; Fig. 4C and 5G) belonging to the intermediate limestone-calcarenite fm (13 + 10 m), followed by a muddier upward interval (68 m) (L9) with bioclastic turbidites (L12b) and sandy limestones (L15) of the upper marly-clayey fm.

In Aspe Terreros section (Log 5) only the lower and upper marly-clayey fms are represented, the sedimentary succession being almost entirely pelitic. However, based on both nature of pelite and coarser interlayers, three intervals may be established. The lower interval (12 m) consists greenish mudstones (L9) with terrigenous (L12a) and bioclastic (L12b) gravity flow deposits. The middle interval (41 m) consists of light greyish soft marls (L9) with disrupted interlayers of tabular to lenticular competent marly-limestone beds, containing olistoliths of different dimensions from cubic decimeters to meters (Fig. 3E and 5H). The two lower intervals probably belong to the lower marly-clayey fm. The features of the second interval correspond with an olistostrome. The third interval (99 m), pertaining to the upper marly-clayey fm, is again made of greenish grey mudstones (L9) with bioclastic turbidites (L12b).

4.1.2. Murcia Sector

All measured sections in Murcia Sector belong to Internal Prebetic (Fig. 1).

El Carche section (Log 6) was previously studied by Guerrera et al. (2014) in La Replana section, only less than a third being logged for this paper (Fig. 2). Based on published data, the succession is more than two third (240 m) constituted by greenish-yellowish clays and marls (Pinoso Marl Fm) with interlayers of sandstones (facies E1 of Guerrera et al., 2014), corresponding to the lower marly-clayey fm. Our data shows that the upper third (intermediate limestone-calcarenite fm) can be divided in two intervals, the lower (67 m) with massive pink to light pink limestones of L4 (Fig. 4D) and L5 facies and the upper (30 m) with L1 type limestone and mudstones (L9).

La Pila section (Log 7) was also studied by the mentioned authors and during this work. The main part of succession (ca 350 m) belongs to Rasa Sandstone Fm (Guerrera et al., 2014), corresponding to the lower marly-clayey fm. This interval is overlain the intermediate limestone-calcarenite fm, consisting of: 10 m of conglomerate and pebbly sandstones of L11, followed by 35 m bedded limestones with LBF (L2, L1, and L3 facies) and >50 intraformational breccia (L10) of same limestone in top. A terra-rosa-like facies (L14) is developed on breccia.

In La Campanera section (Log 8) only the intermediate limestone-calcarenite fm (ca 90 m) is exposed. In the lowermost part, an interval consisting of 3 m of dolomitized sandstones and microconglomerates and 8 m of continental red-beds (L14) is recognized. After 33 m covered, follow 12 m thick brecciated limestone (L10) with interlayers of limestone with quartz grains (L15) (Fig. 3F) and massive limestones (L5, L2 and L1 types) (Fig. 5E) overlain by > 37 m of thick bedded massive limestone with LBF (L3, L2, and L1) (Fig. 5D), brecciated limestones of

Fig. 3. Some representative field photos of the studied sections: A. Intermediate limestone-calcarenite fm in the lower part of the Ibi section (Alicante Sector); B. The olistostrome in the Upper marly-clayey fm in the Aspe section (Alicante Sector); C. Intermediate limestone-calcarenite fm in the El Carche section (Murcia Sector); D. Lower marly-clayey and intermediate limestone-calcarenite fms in the La Pila section (Murcia Sector); E. Upper marly-clayey fm in the Nablanca section (Granada Sector); F. Intermediate limestone-calcarenite fm in the Huescar road section (Granada Sector); G. Intermediate limestone-calcarenite fm in the Arroyo Cerezo section (Jaén Sector); H. Intermediate limestone-calcarenite fm in the Cañada Hermosa section (Jaén Sector).

L4 and L5 types, and more frequent interlayers of limestones with Qz grains (L15). Thin reddish sandy marls (L14) are also observed. Cycles of L2/L3-L1 L3-L1-L14 or L2/L4-L13 can be distinguished.

La Puerta section (Log 9) is more than 540 m stratigraphic thickness, but less than half exposed (mostly belonging to the intermediate limestone-calcarenite fm), being in a forested area. In the lower tenth of this section, two intervals can be defined. The lower (ca 33 m) is a coarsening upward, mostly terrigenous, deposit (L9, L11) with interlayers of limestone with terrigenous pebbles. The upper (30 m) consists of sandy to pebbly limestones, sometime bioturbated, with nummulitids (L2) or alveolines (L1). The terrigenous component increases upward.

In the unexposed interval (>340m) a short outcrop (8 m) with algal limestones (L4) was observed. The last >140 m of this sedimentary succession are better exposed and allowed one to define three intervals. The first one (43 m), mostly terrigenous, consists of three coarsening upward units from the mudstone of L9 to bioclastic sandstones (L11) and sandy limestones of L15 (Fig. 4H) succeeded by 11 m of sands with

Fig. 4. Details of some relevant sedimentary facies defined in the studied area: A. Alveolina limestone (L1) in Section 9 (La Puerta); B. Nummulite limestone (L2) in Section 3 (Onil); C. (big-size) Nummulite limestone (L3) in Section 4 (Onil Quarry); D. Algal limestone (L4) in Section 6 (La Carche); E. Sandy mudstone (L9) with bioturbation in Section 10 (Nablanca); F. Sandstones (L11) with concretions with plant remains in Section 9 (La Puerta); G. Dolomitized limestone (L13) with "ghost" fossils in Section 4 (Onil Quarry); H. Limestone with terrigenous clasts (L15) in Section 9 (La Puerta).

concretions (Fig. 3G and 4F) and conglomerates (L11). The second interval (87 m) begins with thick (38 m) to thinner (11 m) bedded limestone with LBF, whose fossil content changes upward from mainly L2 and L3 facies to L1, some of the contained alveolines being exceptionally big (B-forms). It is followed by 21 m of thick bedded brecciated limestones (L10) in whose clasts the limestone with alveolines (L1) can be recognized. In the upper third of the brecciated unit, exceptionally big size alveolines occur (Fig. 4A). Big size nummulitids can be seen in the mid part of interval. The interval ends with thick bedded limestones (17 m) with LBF (L1 and L2) and miliolids (L6), as well as bivalves and echinoids. The succession is closed by ca 13 m of sandy limestones (L15) with interlayers of micritic limestones (L7) and limestone with miliolids (L6).

4.1.3. Granada Sector

In Granada Sector the two measured sections belong to Internal Prebetics.

Nablanca Section (Log 10) of about 215 m thick consists of four intervals in which two types of units recurrently occur, limestone and mostly mudstones. The first type (15 and 44 m, respectively) consists of

Table 1
The three defined formations with their predominant lithofacies.

Formation	Lithofacies	Description
intermediate limestone-calcarenite fm	L1	Alveolina limestone
	L2	small-size nummulite limestone
	L3	big-size nummulite limestone
	L4	algal limestone
	L5	coral-rich limestone
	L6	miliolid limestone
	L7	micritic limestone (gastropods and bivalves)
	L8	marshy clays-marls and limestones
lower and upper marly-clayey fm	L9	marine clays-marls (with or without turbidites)
intermediate limestone-calcarenite fm	L10	intraformational breccias
	L11	marine sandstones and conglomerates
lower and upper marly-clayey fm	L12	turbidites
intermediate limestone-calcarenite fm	L13	dolostone and dolomitized limestone
	L14	karstic red clays and continental red-beds
	L15	limestones with terrigenous grains and clasts

algal limestone (L4) with rhodoliths and Solenomeris (Fig. 5F) and sandy limestone (L15) together with limestone with nummulitids (L2). In the second type (65 and 91 m, respectively), on the mudstone background (L9), interlayers of sandstones (L11) and calcarenites occur (Fig. 3D and 4E). Only the uppermost interval of intermediate limestone-calcarenite formation corps out (ca 20 m), being followed by upper marly-clayey fm which represents most of the sedimentary succession.

In Huescar Road section (ca 45 m), three intervals can be recognized. After few meters of greyish mudstone (of lower marly-clayey fm), the middle interval (ca 16 m) consists mainly of thick bedded bioturbated algal limestones with LBF (L4, Fig. 5A) and a lenticular body of massive coral-rich white limestone (L5) (Fig. 3C) both pertaining to the intermediate limestone-calcarenite fm. In the upper interval, thick bedded limestones with LBF (L1 type) occur (>15 m). The limestone units (intermediate limestone-calcarenite fm) are separated by 13 m of greyish mudstone (L9).

4.1.4. Jaén Sector

In Jaen Sector, two sections of Internal Prebetics were measures eastward of Santiago de la Espada (Fig. 1B) where only the intermediate limestone-calcarenite fm is represented.

Two intervals can be distinguished in Arroyo Cerezo section (Log 12). The lower one (18 m) consists mainly of limestone and some sandy limestones with small LBF (L2, L4, and L6 facies). It is succeeded by 12 m of algal limestone (L4) and, subordinately, limestone with LBF (L2 and L1), replaced by sandstones with miliolids (L11) toward the upper part of interval. The section top is highly weathered (L14).

In Cañada Hermosa section (ca 100 m), a 6 m lower interval with limestones with LBF (L2, L1) is followed upward by 74 m rather poorly exposed soft light grey marls (L8) with interlayers of white micritic limestones (L7) and limestones with miliolids (L6, Fig. 5C). The upper >15 m of this section consists of a lime mudstone (L8 type) overlain by a quartzarenitic interval with interlayered muddy levels topped by dolostone with unidentified “ghost” fossils (Fig. 5B).

A synthetic representation of the main microfacies recognized in the studied sections is shown in Fig. 5.

4.2. Prebetic Paleocene-Eocene stratigraphic formations and age

As we mentioned above, we propose three informal lithostratigraphic units for the Paleocene-Eocene of the Prebetic Domain, namely: (1) a lower marly-clayey fm; (2) an intermediate limestone-calcarenite fm (absent in Aspe-Terreros section); and (3) an upper marly-clayey fm. In the literature, according to the sectors, for these formations have been used local names. As such, the lower marly-clayey fm was defined in the Murcia sector as the Pinoso-Rasa Fm (Guerrera et al., 2014) and coincides with the marly-clayey interval of the lower part of the Huescar Road section and the Puerto de la Losa Fm in the Granada-Jaén sector (Dabrio, 1972; Álvarez-Suárez and Dabrio, 1974; Pujalte et al., 2010). The intermediate limestone-calcarenite fm was called Miñana Fm in the Murcia sector (Guerrera et al., 2014) and Cañada Hermosa Fm in the Granada-Jaén Sectors (Dabrio, 1972; Álvarez-Suárez and Dabrio, 1974). The upper marly-clayey fm coincides with the upper part of the Nablanca Fm (Dabrio, 1972; Álvarez-Suárez and Dabrio, 1974) in the Granada-Jaén sector. Considering that the former formation names were local and not always represented in all sectors, we prefer to use the proposed informal lithological names for the three formations. These stratigraphic formations are diachronous (Fig. 6) and will be considered separately in the next subsections of this work, considering the oldest and the youngest ages for the base and the top of each one. More information regarding the cited taxonomic species are given in Supplementary Material A2, while in the Supplementary Material A3 a Paleocene-Eocene chronostratigraphic framework of the studied area based on the main LBF, planktonic foraminifera (PF), and calcareous nannofossil (CN) assemblages is shown. Finaly, in the Supplementary Material A4 images of the most representative taxa of planktonic foraminifera, LBF and calcareous nanoplankton are presented in three plates.

4.2.1. Age of the lower marly-clayey fm

We have dated this interval with planktonic foraminifera, calcareous nannoplankton as well as with LBF (Fig. 6; Supplementary Materials A2 and A3). The oldest levels of this formation are exposed in La Pila and El Carche mountains (Murcia sector) and in the section of Huescar road (Granada sector). In La Pila and El Carche sections, on Maastrichtian deposits (samples P6-17, C7-C9; Guerrera et al., 2014), the first Cenozoic levels (P22–23, C10) contain *Acarinina soldadoensis*, *Morozovella acuta*, *M. aequa*, *M. velascoensis*, and *Globanomalina chapmani*. Similar assemblages are also found in Huescar Road where basal levels (EP252) show the couple *Globanomalina pseudomenardii* and *Acarinina soldadoensis* restricted to the P4c of the upper Paleocene. To the top (EP255), *Acarinina angulosa*, *Morozovella aequa*, *Morozovella subbotinae*, and *Morozovella gracilis* are present. These assemblages characterize a P4c-E5 biostratigraphic interval, spanning the Paleocene-Eocene transition and, at the same time, suggest the existence of an about 10 Ma gap, covering most of the Paleocene. The range of the lower marly-clayey fm varies by sector. The greatest geochronologic extension is observed in the Murcia sector, in La Pila and El Carche mountains. In La Pila section, the mudstone levels right below the marine sandstones and conglomerates giving pass to the calcareous units of the intermediate limestone-calcarenite fm contain planktonic foraminifera assemblage (Pila-22, EP1-2) characteristic for upper Ypresian (Zone E7), with *Acarinina pentacamerata*, *A. bullbrooki*, *A. cuneicamerata*, *Igorina broedermanni*, *Morozovella aragonensis*, *M. caucasica*, *Pseudohastigerina micra*. Between Sierra de La Pila and Sierra of El Carche (Garrapancha section; Guerrera et al., 2014), the highest marly levels contain *Acarinina praetopilensis*, *Globigerinatheka subconglobata*, *Subbotina corpulenta*, *S. eocaena*, suggesting a lower-middle Lutetian (zonal range E8-9). The LBFs collected from sandstone interbeds in the formation upper part (EP4-5) indicate SBZ11-12 of middle-upper Cuisian. LBFs of SBZ11 in this sector are represented by *Nummulites praelaevigatus*, *N.* aff. *manfredi*, and *Assilina placentula.* SBZ12 was recognized only in El Carche section, being characterized by the ‘cf.’ presence of *N. campesinus*, *Ornatorotalia subblobata*, and *Medocia blayensis*. The calcareous nannoplankton in studied samples was scarce, only from Huescar Road section (EP256 and EP261) an association with *Ericsonia formosa*, *Sphenolithus editus*, *S. spiniger*, *Zygrhablithus bijugatus*, *Reticulofenestra bisecta*, *R. umbilica*, *R. daviesii*, and *Micrantholithus excelsus* (NP13/NP15 zones) has been

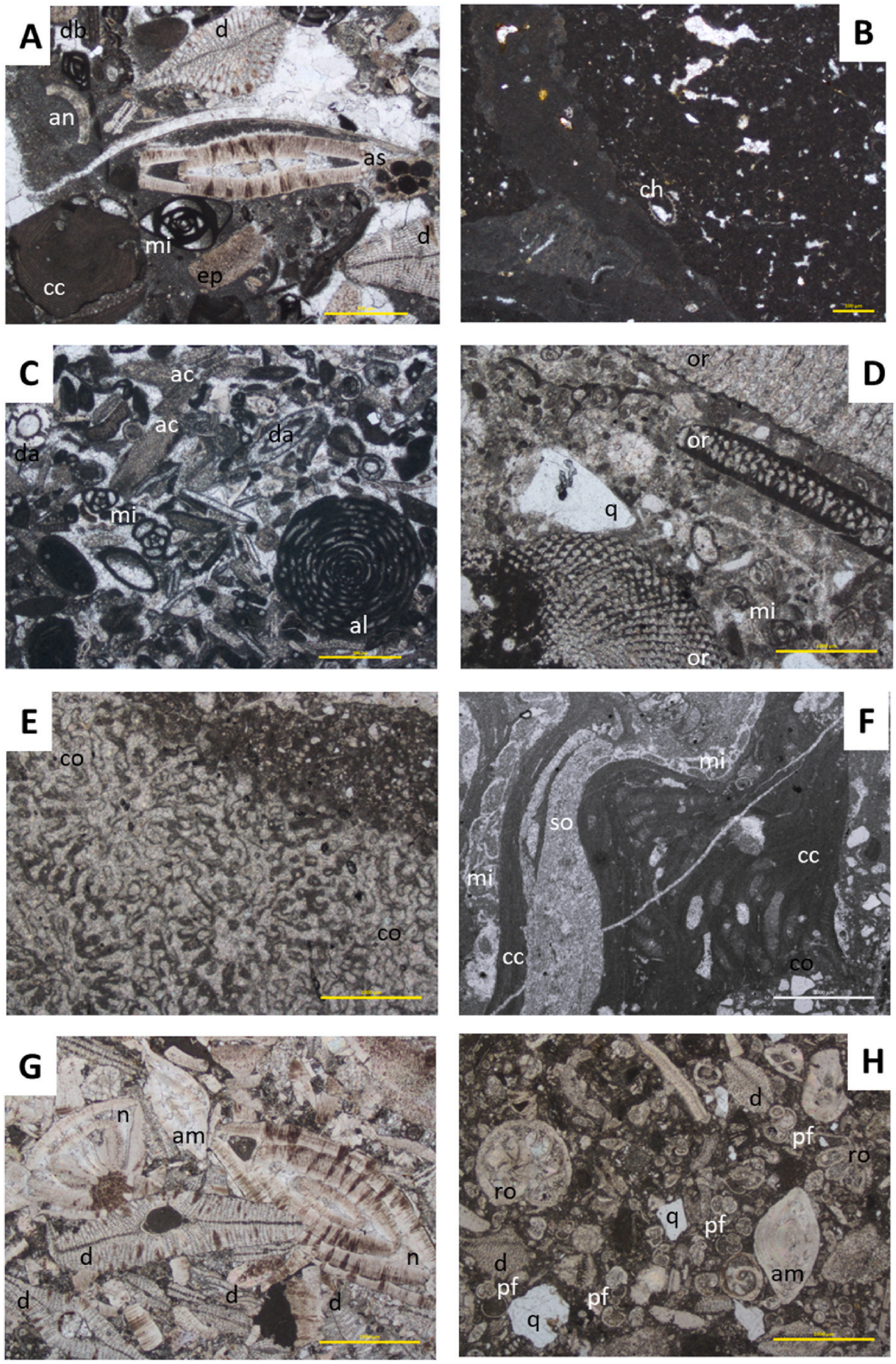

Fig. 5. Photomicrographs of main microfacies of the Paleocene-Eocene Prebetics. Paleocene: A) Mf-1 (middle ramp facies), sample EP 254 (log 11, Huéscar road section). Middle Eocene: B) Mf-2 (marshy marly facies), sample EP 223 and C) Mf-3 (acervulinid-dasycladal inner ramp facies), sample EP 222 (log 13, Cañada Hermosa section); D) Mf-4 (Orbitolites-rich seagrass meadow facies), sample EP 162 and E) Mf-5 (coral-reef facies), sample EP 160 (log 8, La Campanera section); F) Mf-6 (rhodolith-solenomerid maërl facies), sample EP 208 (log 10, Nablanca section); G) Mf-8 (hyaline LBF-rich middle ramp facies), sample EP 109 (log 4, Onil Quarry section); H) Mf-8 (planktic foraminifer-rich open marine facies), sample EP 84: olistolith (log 5, Aspe-Terreros section). Scale bars: Fig. 1 and 500 mm; Fig. 2 and 100 mm; Figs. 3–8, 1000 mm.

Key: ac, acervulinid; al, alveoline; am, amphistegine; an, annelid; as, assiline; cc, crustose coralline algae; ch, charophyte; co, coral; d, discocycline; da, dasycladacean algae; db, *Distichoplax biserialis*; ep, echinoid plate; m, miliolid; mi, miniacine; n, nummulites; or, orbitolites; pf, planktic foraminifer; q, quartz; r, rotaliid; so, solenomerid.

determined, indicating upper Ypresian-Lutetian. Based on dataset mentioned above, the lower marly-clayey fm deposited from the latest Paleocene to the early Lutetian. In the lower part of Aspe Terreros section a turbiditic succession with an olistostrome containing olistoliths was detected. LBFs (EP80 and 84) indicate ages between SBZ8 and SBZ11 (late middle Ilerdian to middle Cuisian). Particularly is interesting the sample EP80a coming from one of the bioclastic turbidite (Fig. 2), dating the SBZ8 late middle Ilerdian with: *Nummulites spirectypus*, *N. exilis*, *N. atacicus*, *N. globulus laxiformis, Assilina canalifera*, and *As. ammonea ammonea.* The Ilerdian is an interval usually missing in the Betic Cordillera due to the early Paleogene tectonics in the area and the following Cuisian erosion (Guerrera et al., 2006, 2014;

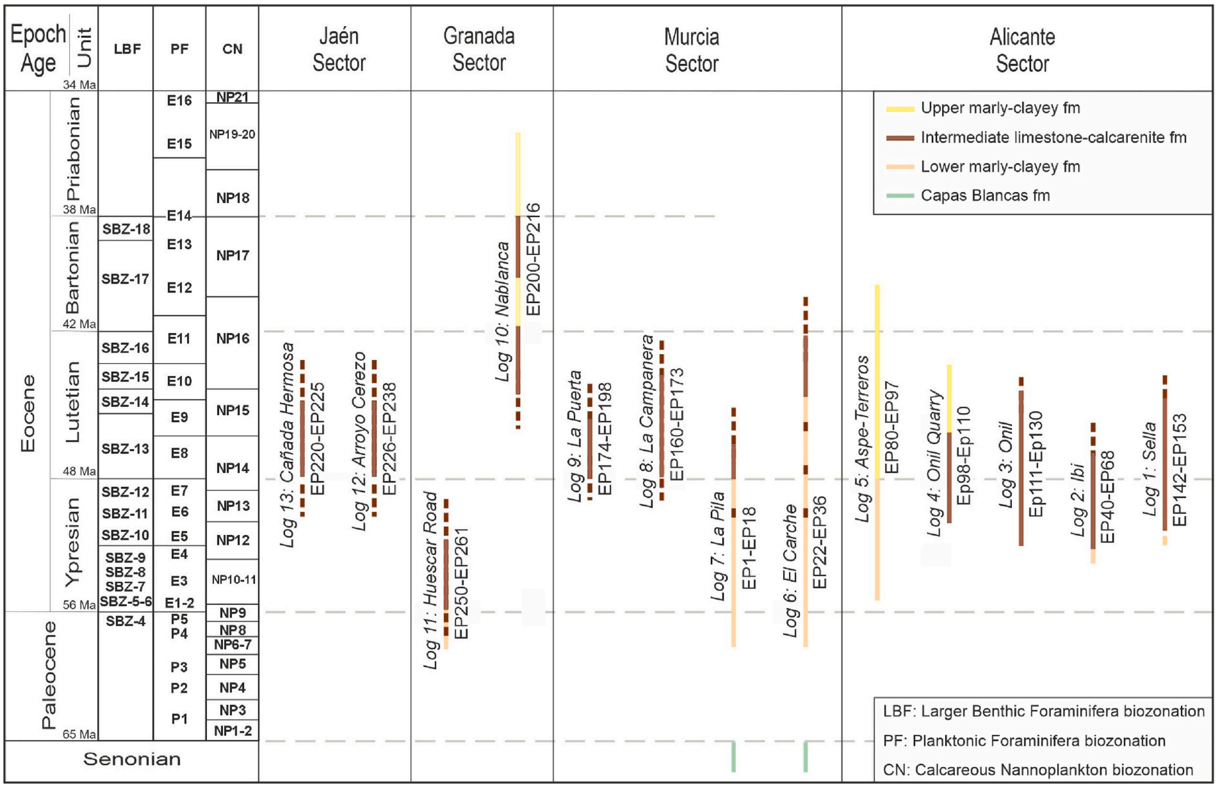

Fig. 6. Chronostratigraphic chart with the age-range of the studied successions.

Martín-Martín et al., 2020c), so the sampled bioclastic turbidite may be one of the few known vestige of a destroyed older (Illerdian) platform.

4.2.2. Age of the intermediate limestone-calcarenite fm

The extent of the limestone-calcarenite fm varies also in the four sectors. Biochronostratigraphic data of this unit are based on LBF contents, mainly alveolinids, nummulitids, and large rotaliids being used (Fig. 6; Supplementary Materials A2 and A3). In the Alicante sector, the oldest age of the formation was proved in Ibi (EP41) and Onil (EP120) sections, corresponding to the middle Cuisian (SBZ11) while the youngest in the Sella section (EP146-149) where it is middle Lutetian (SBZ14-15?). SBZ11 (middle Cuisian) is represented in this sector by: *Nummulites cantabricus*, *N. praelaevigatus*, *N.* aff. *manfredi*, *N. pavloveci*, *N. distans*, *N. irregularis*, *N. archiaci*, *N.* aff. *formosus*, *N. pustulosus*, *Assilina placentula*, *As. laxispira*, *As. escheri*, *As. marinelli*, *As. karreri*, *Alveolina cosigena*, *Al. distefanoi*, *Cuvillerina vallensis*, *Gyroidinella levis*, and *Granorotalia sublobata.* SBZ12 (upper Cuisian) has been recognized in Ibi (EP45-48) and Onil Quarry (EP101) sections, and doubtful in the Onil section (EP125-130). A 'confer (cf)' assemblage for SBZ12 was recognized only in thin sections, consisting of: *N. campesinus*, *N. manfredi*, *N. praediscorbinus*, *As. cuvillieri*, *As. maior*, *As.* aff. *praespira*, *Al.* sp. aff. *violae*, *C. vallensis*, and *G. levis.* SBZ13 (lower Lutetian) has been recognized in Ibi (EP49-59) and Sella (EP142-145) sections. The assemblage for this zone is characterized by the first occurrence of *Fabiania cassis* and the presence of *N. obesus*, *N. lehneri*, *N. alponensis*, *N. migiurtinus*, *N. praediscorbinus*, *N. praebullatus*, *As. praespira*, *Al. stipes*, *Orbitolites complanatus*, *Rotalia trochidiformis*, *G. eocenica*, *Neorotalia litothamnica*, and *Medocia blayensis.* Finally, SBZ14 (lower middle Lutetian) has been only recognized in Sella section (EP146-149). The assemblage for this zone is characterized by the first occurrence of *Sphaerogypsina globulus*, *Sivasina egribucakensis*, and *Gyroidinella magna*, as well as by the presence of *N.* aff. *millecaput*, *N. boussaci*, and *N. migiurtinus. N.* aff. *bullatus* in the samples from the upper part of this section could be compatible with the SBZ15 (upper middle Lutetian), according to Silva-Casal et al. (2021).

In the Murcia sector, the oldest age of this formation is found in La Puerta (EP174 to EP186), Campanera (EP160-164), and La Pila (EP6) sections, corresponding to the lower Lutetian (SBZ13), while the youngest in La Campanera section (EP173), presumably corresponding with the middle Lutetian (SBZ15). The SBZ13 is recognized in all sections of this sector (EP180 to EP186, EP160 to EP164, EP6 to EP11), by: *N. lehneri*, *N. gallensis*, *N. laevigatus*, *N. praelorioli*, *N. praebullatus*, *N. praediscorbinus*, *As.* cf. *spira*, *As. parva*, *Al. stipes*, *Al. tenuis*, *Al. kieli*, *Al. stercusmuris*, *Glomalveolina minutula*, *O. complanatus*, *Praerhapydionina* aff. *delicata*, and the same association of rotaliids as that mentioned for the Alicante sector. SBZ14 is represented in La Pila (EP12-18), La Campanera (EP168-172), and La Puerta (EP187-195) sections, being characterized by the first occurrence of *Sphaerogypsina globulus* and the presence of *N. aspermontis*, *N. beneharnensis*, *N. gratus*, *N.* aff. *carpenteri*, *N. boussaci*, *N.* aff. *millecaput*, *N. migiurtinus*, *N. discorbinus*, *As. praespira*, *Al. elliptica*, *Al. elliptica nuttalli*, *Al. munieri*, *Al. tenuis*, *Al. stercusmuris*, *Al. kieli*, and a rotaliid assemblage like that in the Alicante sector. The presence of *N.* aff. *bullatus* in the samples (EP173) from the upper part of La Campanera section may indicate the SBZ15.

In the Granada sector, the oldest age of the formation is found in the Huéscar road section, where a Paleocene assemblage was recognized (EP253-254) by the abundant presence of the red algae *Distichoplax biserialis* and the LBF assemblage with *As. yvettae*, *As. azilensis*, *Redmondina* sp. aff. *henningtoni*, and *Miscellanea minor*, corresponding to the SBZ4 zone (upper Thanetian). The oldest Eocene deposits with LBF in this section (EP256-261) belong to lower Lutetian (SBZ13) with an LBF assemblage consisting of: *N. obesus*, *N. praelorioli*, *N. migiurtinus*, *N. praediscorbinus*, *N. praebullatus*, *Al. levantina*, *Al. tenuis*, *Al. stercusmuris*, *Al. boscii*, *O. complanatus*, *F. cassis*, *N. litothamnica*, and *G. eocaenica.* The youngest age of the formation is represented in a calcareous interval interfingered in the upper marly-clayey fm in the Nablanca section (EP206-216) where Bartonian is proved by LBFs of SBZ17-18, characterized by the first occurrence of *N.* cf. *garganicus*-

hormoensis, *As.* sp. aff. *schwageri*, *Silvestriella tetraedra*, *Korobkovella grosserugosa*, and *Victoriella conoidea.* There are also *F. cassis*, *S. globulus*, *G. magna*, and *N. litothamnica.*

In the Jaén sector, the oldest age of the formation is the same for the two sections studied (Arroyo Cerezo and Cañada Hermosa) and corresponds to the lower Lutetian (SBZ13), while the youngest is middle Lutetian (SBZ14-15?), the later especially in the Arroyo Cerezo section. SBZ13 zone in this sector (EP220-222; EP226-233) is supported by: *N. lehneri*, *N.* cf. *gallensis*, *N. laevigatus*, *N. praelorioli*, *N. alponensis*, *N. migiurtinus*, *N. praediscorbinus*, *N. praebullatus*, *As.* aff. *tenuimarginata*, *Al. tenuis*, *Al. boscii*, *O. complanatus*, *F. cassis*, *N. litothamnica*, and *G.* cf. *eocaenica.* SBZ14 (EP223-225; EP231-236) is characterized by the first occurrence of *Sphaerogypsina globulus* and the presence of *N. beneharnensis*, *N. gratus*, *N. discorbinus*, *Al. fusiformis*, *Al. stercusmuris*, *Al. tenuis*, *Al. boscii*, *O. complanatus*, *F. cassis*, *R. trochidiformis*, *N. litothamnica*, and *G. magna.* The presence of *N.* aff. *bullatus* in the higher samples of the Arroyo Cerezo section (EP237-238) could indicate the SBZ15. In Supplementary Material 2, the LBF assemblages for each SBZ in the sectors analyzed are shown.

No direct biostratigraphic data have been obtained from the planktonic foraminifer analysis of this formation to allow its datation. However, its age is constrained by the ages of clayey-marly formations in between it is interbedded. In addition, in Aspe-Terreros area, belonging to Alicante sector but closest to Murcia, the greenish mudstones with bioclastic turbidites (EP81-82) of the upper part of the lower marly-clayey fm, contain an assemblage of lower Lutetian (E8-E9). Significant species, as *Acarinina praetopilensis*, *A. cuneicamerata*, *A. bullbrooki*, *Morozovella aragonensis, M. crater*, *M. caucasica, Morozovelloides crassatus* and *M. coronatus,* are present.

In Onil Quarry, this formation must be Cuisian to middle Lutetian, as the first overlying muddy levels (EP99-101) yielded *A. praetopilensis*, *A. cuneicamerata*, *A. bullbrooki*, *M. crater*, and *Parasubbotina inaequispira*, belonging to zone interval E8-E10 from the Lutetian. However, in Nablanca, muddy levels over the calcareous formation (EP211) contain a planktonic foraminifer assemblage (see below) characterizing a zonal interval E13-E14 of the upper Bartonian-lower Priabonian, which must be considered the youngest possible age of the formation in this area.

Consequently, in most of the cases, the maximum range of the intermediate limestone-calcarenite fm extends from the middle Cuisian to the middle Lutetian, locally going down to upper Thanetian (upper Paleocene) or up to lower Bartonian in the Granada sector.

4.2.3. Age of the upper marly-clayey fm

We have dated this interval with planktic foraminifera but also with calcareous nannoplankton (Fig. 6; Supplementary Materials A2 and A3). First deposits of this formation occur in continuity with the underlaying calcareous formation. In the Onil Quarry, the calcareous fm is Cuisian-lower Lutetian (see Sect. 4.2.2). In the upper marls of this section (EP104 and EP101), a calcareous nannoplankton association with *Sphenolithus radians*, *Ericsonia formosa*, and *Discoaster* cf. *D. kueperi*, belonging to the Ypresian-Lutetian without precision was identified. In Nablanca section, the upper marly-clayey fm begins in the Bartonian (EP200-204). The highest analyzed sample (EP211) contains a planktonic foraminifer association made of *S. eocaena*, *S. corpulenta*, *Pseudohastigerina micra, Globigerinatheka semiinvoluta*, *Turborotalia increbescens*, *T. pomeroli*, and *T. cerroazulensis.* This assemblage, in which the genera *Acarinina*, *Morozovella*, and *Morozovelloides* are absent, indicates a limited zonal interval, E13-E14, corresponding to the upper Bartonian-lower Priabonian. Based on calcareous nannoplankton, the marly intervals of this section (EP200-EP212) are characterized by the presence of *Reticulofenestra bisecta*, *Ericsonia formosa*, *Pedinocyclus larvalis*, *Sphenplithus moriformis*, *Reticulofenestra daviesii*, and *Discoaster* cf. *D. barbadiensis*, indicating NP17-NP20 (Bartonian-Priabonian) without more precision. As mentioned in Sect. 4.2.2, in Nablanca section there is an interfingering of the intermediate limestone-calcarenite fm dated as Bartonian. In the case of the upper part of Aspe-Terreros section (EP92-EP97), the age of this formation spans from middle Lutetian to early Bartonian (E9 to E13), according to data obtained from planktic foraminifera. E10 (EP92) is proven by the abundant acarininids and morozovelloids, but in absence of morozovellids of *M. aragonensis* group, while E13 (EP97) by the occurence of *Subbotina gortani*, *T. pomeroli* and *T. cerroazulensis*. Also, the calcareous nannoplankton association of *Ericsonia formosa*, *Reticulofenestra umbilica*, and *Chiasmolithus grandis* are indicative of NP16-17 (Lutetian-Bartonian transition).

5. Paleocene-Eocene stratigraphic architecture of the Prebetic Domain

After the gap in the Cretaceous-Cenozoic boundary (Fig. 7), the stratigraphic architecture of the three Paleocene-Eocene formations from the Prebetic Domain shows diachronous boundaries, lateral transitions and interfingerings. The oldest deposits have been dated (upper Paleocene) in sections 6, 7, and 11, being represented by the lower marly-clayey fm which unconformably overlays the Senonian Capas Blancas Fm (Fig. 7). The youngest age (lower Priabonian) is proven in the upper part of the upper marly-clayey fm of section 10 (Fig. 7). The base of the lower marly-clayey fm is upper Paleocene in age, while the top is diachronous and coincident with the base of the overlaying formation (Fig. 7). Both lower and upper bounding surfaces of the intermediate limestone-calcarenite fm are diachronous. The lower one ranges from the Paleocene-Ypresian boundary (section 11) to the middle Lutetian (section 6), while the upper one ranges from Ypresian-Lutetian boundary (section 4) to Bartonian (section 10) (Fig. 7). The intermediate limestone-calcarenite fm is not developed in section 5, the lower and upper marly-clayey formations being in conformity. The base of the upper marly-clayey fm coincides with the top of the underlaying formation (excepting the Nablanca section where Bartonian limestone interfingers with Bartonian-Priabonian upper marly-clayey fm), while the youngest top age is lower Priabonian (section 10, Fig. 7). The diachronism of the three formations can be a result of the inherent sedimentary paleoenvironment (platforms and slopes), but also of tectonic control (subsidence and rising).

The fossil content and lithofacies (Belayouni et al., 2012; Guerrera et al., 2014a; Martín-Martín et al., 2024) indicate that: (1) the lower marly-clayey fm was sedimented on external platform to slope realms according to the marly lithology (in the case of Aspe section with mass flow deposits) and the ratio planktonic/benthonic foraminifera (dominated by planktonic fauna); (2) the intermediate limestone-calcarenite fm represents an internal to mid platform as it is proven by its calcareous or calcarenitic lithology and the presence of LBFs and corals; (3) the upper marly-clayey fm represents again an external platform to slope, having almost the same features as the lower marly-clayey fm as marly lithology and elevate content in planktonic fauna. After a generalized regression during the early-middle Paleocene with possible emersion, a rapid transgression in the late Paleocene created the conditions for carbonate platform development in Prebetic domain. In the following late Paleocene-Eocene time span a regressive-transgressive cycle was recorded. In some of the studied sections, such as Ibi and Cañada Hermosa, terrigenous supply, dolomitization, and emersion are registered after the intermediate limestone-calcarenite fm sedimentation. In Arroyo Cerezo case, limestones are replaced by sands and sandstones. This could indicate the establishment of shallow areas in the Prebetic possible due to tectonic rising where (if not dolomitized) miliolid and alveoline limestones sedimented. Contrarily, areas where the upper marly-clayey fm sedimented during the late Eocene may indicate subsiding areas. The results of the thicknesses analysis presented in the following section will give more support to these observations.

6. Thickness analysis

This analysis must be considered with caution since most of the measured columns are incomplete due to tectonic lamination and/or to

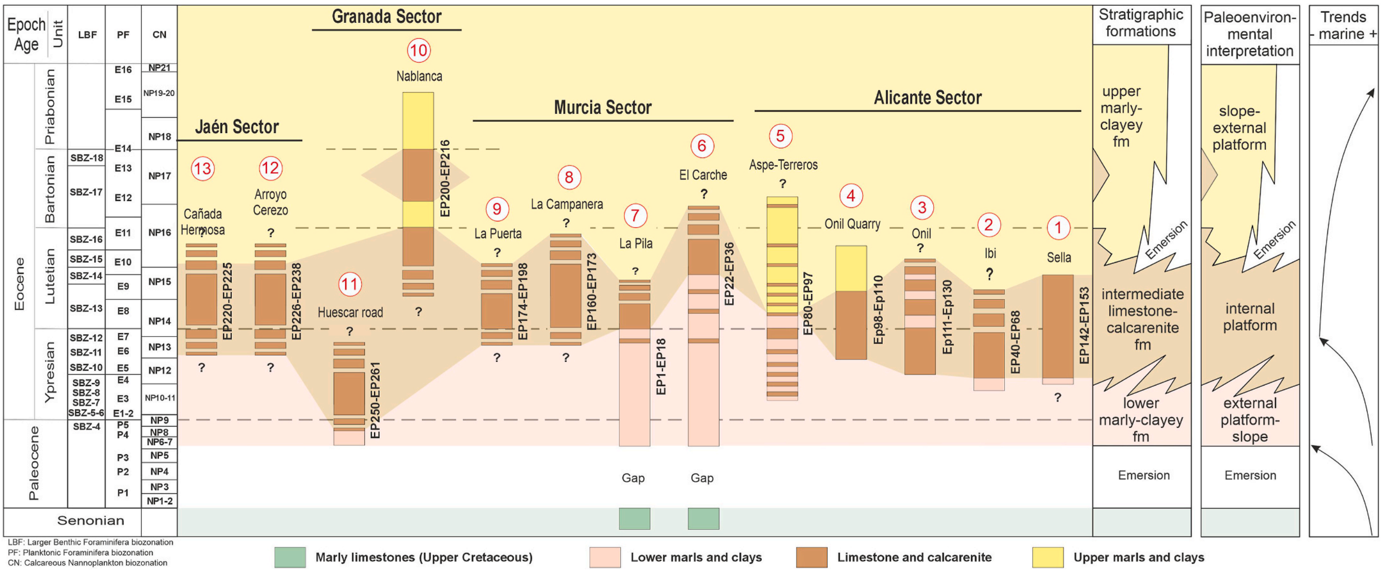

Fig. 7. Paleocene-Eocene stratigraphic architecture of Prebetic domain with biozones, sedimentary realms, and trends.

recent erosion. Here, the measured section thicknesses should be considered the minimum thicknesses in most of the cases either for entire succession or for each formation. For the same reasons, compaction could not be estimated. In most of the studied sections the covering sedimentary successions is not preserved (or not deposited) and the backstripping method can not be applied. Despite these difficulties, important deductions can still be made regarding the relative tectonic movements (relative sinking and rising areas) of the different areas

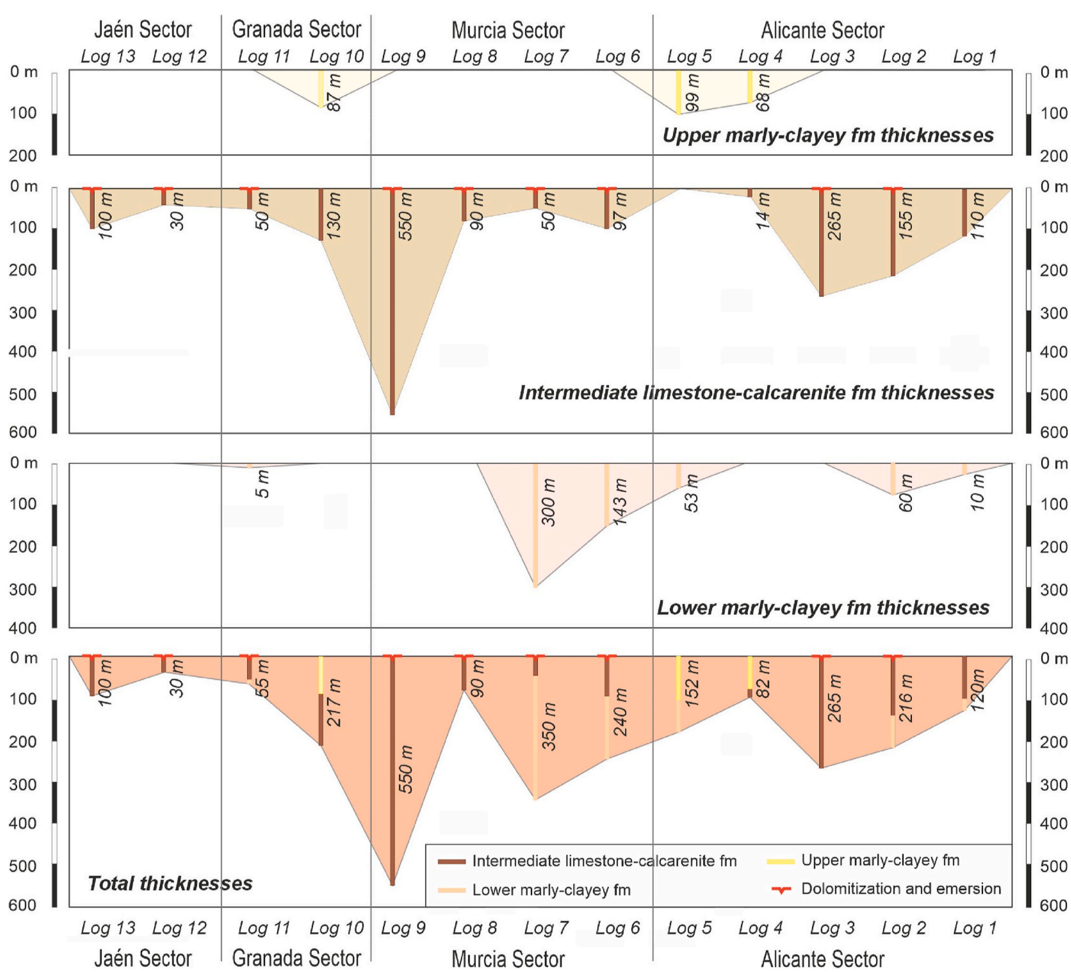

Fig. 8. Compacted thickness analysis of, from top to bottom: the upper marly-clayey fm, intermediate limestone-calcarenite fm, lower marly-clayey fm, and total sedimentary successions. Note: compaction has not been restored.

which can explain the thickness variations in the measured (compacted thicknesses) sections. This analysis has been performed both for total and for each formation thicknesses (Fig. 8).

6.1. Total compacted thickness analysis

The total measured thickness (Fig. 8) vary from 30 m, the thinnest (Log 12 in Jaen Sector), to 550 m, the thickest (Log 9 in Murcia Sector). Log 9 is a very interesting case since it represents almost entirely the intermediate limestone-calcarenite fm. Another thick (ca 350 m) succession was measured is the Log 7 (Murcia Sector), here mostly consisting of the lower marly-clayey fm. Among the thinnest (<100 m) are Logs 4 (Alicante Sector), Log 8 (Murcia Sector), and Log 11 (Granada Sector).

6.2. Lower marly-clayey fm compacted thickness analysis

This formation (mostly upper Paleocene to lower Eocene) is not represented in the whole area (Fig. 8). It does not occur in the logs 3 and 4 (Alicante Sector), logs 8 and 9 (Murcia Sector), 10 (Granada Sector), and 12 and 13 (Jaén Sector). The greatest thicknesses were measured in Murcia Sector in Log 7 (ca 300 m) and Log 6 (143 m), while in the other sectors is less than 50 m. It is likely that the deposits measured in logs 6 and 7 sedimented in a subsiding sector of Prebetic during late Paleocene and early Eocene. This stratigraphic formation was sedimented in deeper water (external platform to slope) as it is proven by the mudstone background with terrigenous turbidite (Pinoso-Rasa Fm in logs 6 and 7) and terrigenous and bioclastic turbidites and olistostromes (Log 5). The interval when it was sedimented was characterized by minor sea level short-term changes superposed on a rather high position of long-term sea level. As such, the major thickness difference between the Alicante Sector and Murcia Sector may not be explained by sea level behaviour, but rather by an active tectonic of the latter, during late Paleocene-early Eocene. At the same time, the lack ot this formation in most of the measured sections (logs 3, 4, 8, 9, 10, 12, and 13) or its very low thickness (logs 1 and 11) may be explained by paleogeographic context (different positions on shallow water platform). It is worth to notice that where this formation is thin, the intermediate formation it thicker.

6.3. Intermediate limestone-calcarenite fm compacted thickness analysis

This formation (mostly lower to middle Eocene) is the most suitable of the three for such analysis (Fig. 8) since, with one exception (Log 5, recording the deepest environment), occurs in all measured sections. Its thickness varies from 14 m (Log 4: Alicante Sector) to 550 m (Log 9: Murcia Sector). Other sections where this formation is thick were measured in Log 3 (265 m), Log 2 (216 m), and Log 1 (115 m), in Alicante Sector, and Log 10 (130 m) from the Granada Sector. In the latter, only the upper part of this formation is exposed. The thicknesses from 30 m to ca 100 m characterize the other sections (logs 6 to 8 from Murcia sector, Log 11 from Granada sector, and logs 12 and 13 from Jaén Sector). Moderate variations in thickness can be explained according to the paleogeographical context in which the successions measured in different logs accumulated (proximal to middle to distal platform), the same cannot be said about major thickness variations (one or even two orders of magnitude). At the same time, when this formation was deposited, the long-term sea level was on high position, the superposed short-term changes, some with important amplitudes, such the one in Cuisian, being a possible explanation for the observed small-scale cycles described in chapt. 4.1. However, they are unlikely to explain the important thickness variations measured in some sections. In this case, it is probable that tectonic subsidence affected Murcia and Alicante Sectors where limestone-calcarenite fm has the biggest measured thicknesses. Therefore, sinking tectonic areas can be likely placed in the thicker sections as logs 9 (Murcia Sector), 3, 2, and 1 (Alicante Sector).

6.4. Upper marly-clayey fm compacted thickness analysis

This formation is the least suitable for thickness analysis because it is missing in most sectors (Fig. 8) either because it did not sedimented, or because it was eroded immediately after sedimentation as a result of the post-Eocene evolution of the Prebetic domain, or much later. For instance, in Log 3 the upper middle Eocene limestones are unconformable overlain by Rupelian marls (not represented in Fig. 2). It does not occur in logs 1, 2, and 3 (Alicante Sector), logs 6 to 9 (Murcia Sector), Log 11 (Granada Sector), and logs 12 and 13 (Jaén Sector). As mentioned above, its absence in certain sectors can be explained based on the paleogeographical context unfavorable for the sedimentation of distal platform-slope deposits. At the same time, it was sedimented mostly during global cooling and sea-level rising after the Middle Eocene Climatic Optimum (41-40 Ma) (Bohaty and Zachos, 2003; Zachos et al., 2008). Where this formation is represented, it is very thin, varying from 68 m, in Log 4 (Alicante Sector), to 87 m in Log 10 (Granada Sector) and to ca 100 m, in Log 5 (Alicante Sector).

6.5. Synthesis to the thickness analysis

The analysis of the total and the intermediate limestone-calcarenite fm thicknesses of studied sections shows a certain correlation. Based on them, relative tectonic sinking areas in comparable times (early-middle Eocene) can be located Murcia Sector (Log 9) and Alicante Sector (Log2). Areas with minor tectonic in sinking could be indicated by the Log 4 (Alicante Sector), Log 8 (Murcia Sector), Log 11 (Granada Sector), and logs 12 and 13 (Jaén Sectors) on a background rather stable by tectonic point of view where both total and limestone-calcarenite formation compacted thicknesses are small. This analysis could indicate contemporaneous relative rising and sinking areas due to local tectonics by faulting or folding.

7. Paleocene-Eocene tectono-sedimentary evolution and trends

The three lithostratigraphic units characterized by lateral and diachronic changes of facies indicate different sedimentary paleoenvironments: the intermediate limestone-calcarenite fm (rich in LBF) mainly represents an internal to middle marine platform, while the two marly-clayey fms, an external platform. In Alicante and Murcia sectors, upper slope depositional environment was also established, the frequent terrigenous and bioclastic turbidites (Log 5 in Alicante Sector and logs 6 and 7 în Murcia Sector) as well as mass-flow deposits (in Log 5) being convincing evidences. As a whole, the generalized regression, known in the Tethys realms at Cretaceous-Paleocene boundary, was recorded as deposits with shallowing upward trends, followed by emersion of the former shallow realms and development of the unconformity with a stratigraphic gap ranging from Maastrichtian to late Paleocene (e.g. Guerrera et al., 2014). The sedimentation resumed toward the end of Paleocene, after the accommodation space was again created as a consequence of relative sea level rise followed re-establishment of the sedimentation environments. The upper Paleocene-Eocene sedimentary succession shows a long term regressive-transgressive trend (Fig. 7). The age differences along the bounding surfaces of the three stratigraphic formations indicate the proximal-distal paleogeographic positions in Prebetic domain of measured sections as well as a certain tectonic influence. As such, in the proximal sections of Alicante sector, the intermediate limestone-calcarenite formation (logs 2 and 3, Fig. 6) of shallow marine environment extends on the widest time-span range. On the other hand, in the distal sections, the two marly-clayey formations time-spans range wider than the intermediate limestone-calcarenite formation (sections 1 to 9 and 12–13, Fig. 6). As such, the sections where the upper part of the lower marly-clayey fm is the youngest (logs 6 and 7, Fig. 6) could indicate a relative tectonic sinking area allowing the establishment and longer preservation of deeper sedimentation area, at least during the Paleocene and early Eocene, that delayed the platform development until the middle Eocene. The sections where the lower part of the upper marly-clayey fm is the oldest (Fig. 6) likely indicate a relative active tectonic sinking also during early-middle Eocene. In these cases, the development of the external platform-slope began earlier (toward the end of the early Eocene). The absence of the upper marly-clayey fm (logs 2–3, 6–9, and 11–13) due to post-sedimentation emersion at the top of the intermediate limestone-calcarenite fm or later could indicate shallow areas of the Prebetic affected by a relative tectonic rising in a period with global cooling and sea-level rising after the Middle Eocene Climatic Optimum (41-40 Ma) (Bohaty and Zachos, 2003; Zachos et al., 2008). Part of this evolution has been regarded in literature as a result of regional tectonics probably related to the Eo-Alpine compressive phase in the Tethyan realms (Guerrera et al., 2006, 2014, 2021; Martín-Martín et al., 2023a, 2023b) where the folding of basement and its sedimentary cover gave rising areas in the anticlines and sinking area in the synclines.

8. Comparison with other Tethyan margins of the central–western Mediterranean chains

As commented in the Introduction, the Paleogene climatic variations gave rise to important paleogeographic changes, among them, the development of carbonate ramps (rich in larger benthic foraminifera and zooxanthellate corals) located in two belts on the margins of the Tethys Ocean. For Paleogene times, recent paleogeographic models (Guerrera et al., 2021; Martín-Martín et al., 2020c, 2021, 2023a, 2023b, 2024; Tosquella et al., 2022) suggest the existence of several oceanic branches or basins in the western Tethys and the transition zone to the Atlantic Ocean. The southern belt in the western Tethys is related to the Maghrebian Flysch basin. The studied Prebetic succession from the South Iberian Margin (S Spain) was part of the meridional belt and related to the South Iberian Margin-Nevado-Filábride-Liguride-Piemontese oceanic branch. In this section a comparison with other Tethyan margins of the central-western Mediterranean area (Scheibner and Speijer, 2008; Höntzsch et al., 2013; Pomar et al., 2017; Müller et al., 2019; Martín-Martín et al., 2020c, 2021, 2023a, 2023b; Tosquella et al., 2022) is performed in order to give a broader perspective to the readers (Fig. 9). The correlated sectors are numbered and located on a paleogeographic index map in Fig. 9. The Prebetic sector (1) is compared with: the more external Subbetic in the same South Iberian Margin (2); the Southern margin of the Mesomediterranean Microplate passing to the Maghrebian Flysch Basin (3); the NW African Margin in the Moroccan Rif located in the transition area of the Maghrebian Flysch Basin to the Atlantic Ocean (4); the North Iberian Margin in the Pyrenean realm of Atlantic influence (5); NE African Margin in the Tunisian Tell in transition area to the Maghrebian Flysch Basin (6); the Sicilian Margin also in transition area to the Maghrebian Flysch Basin (7); and the Adriatic Margin in the Southern Apennines in the transition area of the Maghrebian Flysch to the Ionian basins (8). In many of the cases, the Cenozoic oncoming is associated with a change in sedimentation from hemipelagic marly-limestones (Capas Blancas, Abiod, Scaglia fms) to different kinds of sediments following the unconformity materializing a part of the Paleocene. Also, in most of the cases, a diversification in shallow and deep sedimentary successions is recorded in the correlated margins. These changes can be attributed to the climatic changes, but also to the Eo-Alpine tectonics (Guerrera and Martín-Martín, 2014b; Guerrera et al., 2021). In the evolution of all compared margins a common pre-foredeep (Paleocene-Eocene), followed by foredeep activation during the Oligocene and margin tectonization during the Miocene (Guerrera et al., 2006, 2014, 2021; Martín-Martín et al., 2023a, 2023b) can be recognized. The whole South Iberian Margin (Vera, 2000, 2004; Tent-Manclus, 2003; Martín-Martín et al., 2018a, 2018b; Guerrera et al., 2006, 2014) made by the studied Prebetics (1) and the correlated Subbetics (2) shows the transition from a shallow (Prebetic) to deep

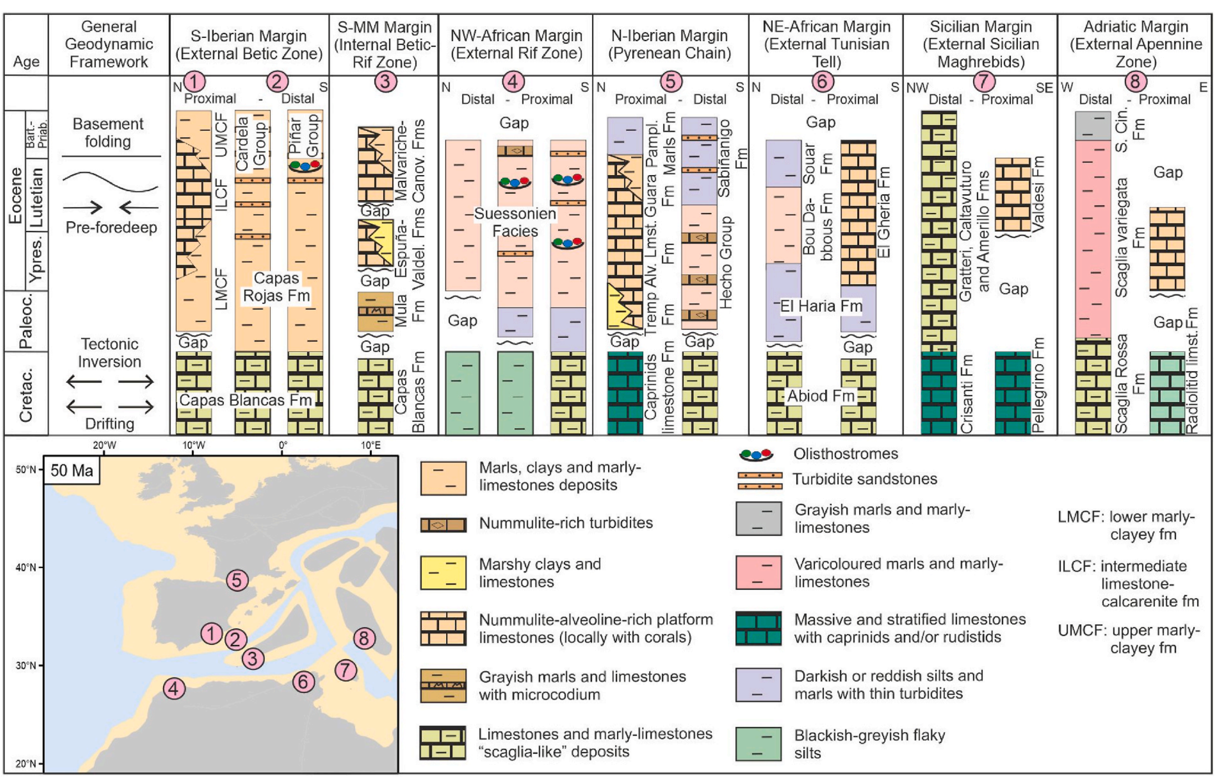

Fig. 9. Stratigraphic chart showing the correlation with other Tethyan margins: (1) Prebetic Domain and (2) Subbetic Domain of the South Iberian Margin; (3) South Margin of the Mesomediterranean Microplate Domain (Internal Betic-Rif Zone: S Spain and N Morocco); (4) NW-African Margin (Moroccan External Rif Zone); (5) North Iberian Margin (Pyrenean Realm); (6) NE-African Margin (Tunisian Tell); (7) Sicilian Margin (External Sicilian Maghrebids, Italy); (8) Adriatic Margin (External Apennine Zone, Italy).

platform (Subbetic). The Subbetics were structured into heights and subsiding areas with olistostrome deposition (Capas Rojas Fm, Cardela and Piñar groups). The Southern margin of the Mesomediterranean Microplate (3) (Malaguide-Ghomaride Domains from Internal Betic-Rif Cordillera, S Spain, N Morocco) is made of LBF and z-coral-rich platforms represented by the Mula, Espuña, Valdelaparra, Malvariche, and Cánovas fms (Martín-Martín et al., 2020c, 2021, 2023a; Tosquella et al., 2022). Similar conditions to those from the Subbetics are recognized in the Moroccan NW African Margin (4) with the Suessonien facies and olistostrome deposits (Martín-Martín et al., 2023b). The Paleogene carbonate platforms were eroded from the southern sector of this margin, the Miocene deposits onlapping the resulted unconformity (Martín-Martín et al., 2022, 2023b). Two kinds of sedimentary successions are also known in the Pyrenean realm (5), a southern shallow succession, represented by the Tremp ('Garumnian facies'), Alveolina, Boltaña and Guara limestones and Pamplona marl fms, and a northern coeval deep succession represented by the Hecho Group and the Sabiñánigo Fm (Puigdefábregas, 1975; Mutti et al., 1985; Remacha et al., 1998; Barnolas et al., 2004; Gil-Peña et al., 2012; Pickering and Cantalejo, 2015; Roigé et al., 2016; Martín-Martín et al., 2001). On the NE African Margin in the Tunisian Tell (6) again two kind of successions are documented (Rouvier, 1977, 1985; Van Houten, 1980; Wildi, 1983; Belayouni et al., 2010, 2012, 2023a, 2023b): the shallow one (el Gheria Fm) and the deep one (El Haria, Bou Dabbous, and Souar fms). The Sicilian Margin (7) had a palaeogeographic and palaeotectonic evolution similar to the Tunisian margin previously described (Catalano et al., 2013; Lentini and Carbone, 2014; Basilone, 2018; Basilone and Di Maggio, 2016; Benedetti, 2019; Henriquet et al., 2020; and references therein) with the Panormide carbonate shelf with LBFs and corals (Valdesi Fm) and the deep-water Imerese Basin represented by the Gratteri, Caltavuturo, and the Amerillo Fms (slope limestones and hemipelagic limestones scaglia-like facies) during Paleocene and Eocene. Finally, on the Adriatic Margin (8) two main domains, located southward and northward of the Ancona-Anzio tectonic line, respectively, are distinguished, with Scaglia Variegata and Cinerea fms indicating deep environment, while the carbonate platforms from Puglia sector, the shallow water one (Guerrera et al., 2015; Vitale et al., 2018).

9. Conclusions

This study based on thirteen sections logged in Paleocene-Eocene sedimentary successions, exposed along the Prebetics of the Betic Cordillera in Alicante, Murcia, Granada, and Jaén sectors, has evidenced the following main important findings:

- The studied sections were measured and sampled for characterizing the sedimentary realms and dating. Fifteen mainly shallow marine or transitional sedimentary macrofacies were defined.
- Three informal diachronous stratigraphic formations were proposed and dated with planktic foraminifera, calcareous nannoplankton, and LBF: (1) a lower marly-clayey fm; (2) an intermediate limestone-calcarenite fm; and (3) an upper marly-clayey fm.
- The base of the lower marly-clayey fm is upper Paleocene in age, while the top is diachronous. Both lower and upper bounding surfaces of the intermediate limestone-calcarenite fm are diachronous, ranging from lower Ypresian to middle Lutetian and from Ypresian-Lutetian boundary to Bartonian, respectively. The base of the upper marly-clayey fm is coincident with the top of the underlaying formation with the exception of the above-mentioned interfingering, while the youngest top age is lower Priabonian.
- The intermediate limestone-calcarenite fm (rich in LBF) mainly represents a shallow water internal to middle marine carbonate platform, while the two marly-clayey fms represent the deeper external platform (and the upper slope in a few cases).
- The diachronism of these three formations reflects climatic-tectonic interference. The top of the intermediate limestone-calcarenite fm is dolomitized in some sections, indicating the emersion of those sedimentation areas in Eocene, in association with tectonic rising, while the areas with marly sedimentation during the late Eocene undergone subsidence.
- A form of thickness analysis was also performed, compacted thicknesses being taken into account, considering the overlying deposits, in most of the cases, lack because of postsedimentation tectonics and/or erosion and the backstripping method could not be applied. A certain correlation is observed between the total sedimentary succession thickness and the intermediate limestone-calcarenite fm thickness of the studied sections. This analysis seems to indicate contemporaneous relative sinking and rising areas along Prebetics due to tectonics.
- The studied Prebetic Domain from the South Iberian Margin (S Spain) was part of the meridional belt of carbonate platforms of the western Tethys and related oceanic branches during Paleocene-Eocene times. A comparison of the tectono-sedimentary findings has been performed with other Tethyan margins and related oceanic branches of the central-western Mediterranean area. In most of the cases, the oncoming of the Cenozoic is associated with a palaeogeographic change from hemipelagic conditions (Capas Blancas, Abiod, Scaglia fms) to shallow water realms after an unconformity associated with a gap materializing an important part of the Paleocene.
- In most of the cases, a similar palaeoenvironmental diversification in shallow and deep realms is recorded in the correlated margins. The diversification of the sedimentary environments can be attributed to the climatic changes, but also to the effects of the compressive Eo-Alpine tectonics giving pre-foredeep conditions in all the compared margins. In the studied area, the compressive tectonic must have affected the basement with its sedimentary cover which folded giving rising areas in the anticlines and sinking ones in the synclines.
- In the case of shallow sedimentary successions, carbonate marine ramps with LBF and z-corals have developed. Comparable gaps in sedimentation are recorded in most of the correlated domains.

CRediT authorship contribution statement

Manuel Martín-Martín: Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Crina Miclăuș:** Writing – original draft, Investigation. **José Enrique Tent-Manclús:** Investigation. **Josep Tosquella:** Writing – original draft, Methodology, Investigation. **Francisco Serrano:** Writing – original draft, Investigation. **José María Samsó:** Investigation. **José Antonio Martín-Pérez:** Investigation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpetgeo.2025.107300.

Data availability

Data will be made available on request.

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