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Revision of the Maastrichtian-Palaeocene charophyte biostratigraphy of the Fontllonga reference section (southern Pyrenees, Catalonia, Spain)

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ABSTRACT

The Fontllonga section is one of the best-known stratigraphic sections wordwide for the study of charophyte biostratigraphy of the Maastrichtian and lower Palaeocene. An updated proposal for the charophyte biostratigraphy of this section is presented after summarizing previous knowledge. The zone of Peckichara cancellata allows the upper Campanian–lowermost Maastrichtian to be characterised in the base of the section (La Maçana Formation). The Microchara punctata biozone represents most of the Maastrichtian (Figuerola Formation). Within this biozone, a Clavator ultimus subzone is proposed to improve characterisation of the lower and middle Maastrichtian. Both the upper and lower boundaries of the Microchara punctata biozone proposed in previous studies are modified based on new occurrences of the index species. A charophyte assemblage belonging to the Dughiella bacillaris biozone is reported for the first time from the middle of the section (Perauba Complex) and provides an age for this unit ranging from the upper Danian to lower Thanetian. A foraminifer assemblage found in the basal marine deposits above the non-marine succession of the Fontllonga section provides new biostratigraphic data to locate the upper boundary of the non-marine succession at least within the upper Thanetian.

KEYWORDS **Charophyta. Chara. Biozonation. Àger Basin. Chronostratigraphy. Iberia. Maastrichtian-Paleocene.**

INTRODUCTION

The sedimentary succession of the Fontllonga section (Àger Basin, southern Pyrenees) contains a complete record of the non-marine Maastrichtian and Palaeocene, and was considered a European reference section for the study of the Cretaceous–Palaeocene charophyte biostratigraphy by Riveline *et al.* (1996). To date, analysis of the Fontllonga section has mainly focused on the position of the Cretaceous/Palaeogene (K/Pg) boundary and on characterisation of the fossil floral and faunal changes across it. Studies include the biostratigraphy of non-marine taxa, such as charophytes (Babinot *et al.*, 1983; Feist and Colombo, 1983; Riveline *et al.*, 1996; Mayr *et al.*, 1999; Villalba-Breva and Martín-Closas, 2013), palynology (Médus *et al.*, 1988; Médus and Colombo, 1991; Fernández-Marrón *et al.*, 2004), gastropods and ostracods (Babinot *et al.*, 1983) and microbialites (Astibia *et al.*, 2012). Additional studies were devoted to systematic vertebrate palaeontology, mostly dinosaurs (Babinot *et al.*, 1983; López-Martínez *et al.*, 2001), magnetostratigraphy (Galbrun *et al.*, 1993) and stable isotope analysis (López-Martínez *et al.*, 1998; Mayr *et al.*, 1999; Domingo *et al.*, 2007; Minelli *et al.*, 2013).

The relatively abundant fossil charophytes in the Fontllonga section have been of prime importance in determining the relative ages of these continental deposits.

After the pioneering biostratigraphic analysis carried out in southern France by Grambast (1962, 1964), Feist-Castel (1975) and Massieux *et al.* (1979), the Àger Basin was the object of several studies that aimed to construct a proper charophyte biozonation of regional importance in Europe. The charophyte assemblages in the Àger Basin were first documented in detail by Feist and Colombo (1983) and Masriera and Ullastre (1990). Later they were calibrated with magnetostratigraphic data by Galbrun *et al.* (1993) who proposed five charophyte biozones for the Upper Cretaceous–lower Palaeocene deposits (*i.e.* the Lower Microchara cristata zone, the Middle Microchara cristata zone, the Lower-Upper Microchara cristata subzone, the Upper-Upper Microchara cristata subzone and the Peckichara toscarensis zone). This local biozonation was then used as a base to characterise the K/Pg boundary in the European charophyte biozonation (Feist in Riveline *et al.*, 1996; Feist in Hardenbol *et al.*, 1998), which was used over a long period of time. This scheme, however, bears some weaknesses, such as the biozone Peckichara sp. 1, with a poorly defined index species, the interval biozone of Microchara cristata which is of difficult use in discontinuous terrestrial outcrops, and unknown charophyte palaeoecological constraints for all index species. Since then, only a few studies have focused on the analysis of the charophyte biostratigraphy and palaeoecology of the Àger Basin. Mayr *et al.* (1999) complemented the study of Early Palaeocene charophytes in the Fontllonga section, and Villalba-Breva and Martín-Closas (2013) studied the upper Campanian–basal Maastrichtian charophytes of the section (La Maçana Formation, Fm.).

The aim of this study is threefold. First, to provide a brief stratigraphic and sedimentological account of the non-marine deposits of the Fontllonga section, Àger Basin, from the top of the Campanian–Maastrichtian nearshore marine Bona Fm. to the Ypresian (lower Eocene) marine Alveolina Limestone of the Cadí Fm., in order to document the palaeoenvironmental context of the charophyte assemblages. Second, to provide new biostratigraphic (charophyte and foraminifer) data. Finally, to propose a new local charophyte zonation for the Àger Basin considering the previous European biozonation and integrating the local results from two other southern Pyrenees basins (Vallcebre and Coll de Nargó) recently published by Vicente *et al.* (2015, 2016).

GEOLOGICAL SETTING

The oblique collision between the Iberian and European plates resulted in an Alpine fold-thrust belt forming the Pyrenees. The collision and the anticlockwise rotation of the Iberian plate were responsible for the closing and continentalisation of the basin (Capote *et al.*, 2002). The polarities of the infilling of the Pyrenean basins were South to North and East to West (Villalba-Breva and Martín-Closas, 2013). Due to the thrusting event, three superimposed thrust sheets were formed. The southern thrust sheet, called Serres Marginals, is bounded to the north by the Montsec thrust and to the south by the Ebro Foreland Basin (Muñoz *et al.*, 1986). The piggy back Àger Basin is a very asymmetrical syncline formed after the internal subdivision of the Serres Marginals. This subdivision resulted in the formation of three minor thrusts. The northern thrust, called Àger-Montroig, transported piggy-back the Àger Basin to the south. The stratigraphic succession is about 2500m thick and is formed of marine and continental deposits from the Triassic to the Palaeogene (Saula and Samsó, 1996).

According to Caus and Gómez-Garrido (1989), the studied continental deposits range in age from the Campanian to the Thanetian. A short terrestrial recurrence is also reported near the Palaeocene–Eocene boundary which includes the Palaeocene–Eocene Thermal Maximum (Minelli *et al.*, 2013). The Upper Cretaceous–Thanetian non-marine deposits have traditionally been called "Garumnian" facies (Leymerie *et al.*, 1962) and represent a regional regression overlying the last Upper Cretaceous nearshore marine deposits. The stratigraphic subdivision of these deposits has been the object of different proposals. Colombo and Cuevas (1993) described the stratigraphy and sedimentology of the Àger Basin in detail and named the continental deposits of Garumnian facies Fontllonga group, proposing four formal units, from base to top (Table 1): La Maçana Fm., Figuerola Fm., Millà Fm. and the Perauba Complex. Later Rosell *et al.* (2001) subdivided the non-marine succession of the southern Pyrenees into four lithological units: i) the basal Grey Unit (lagoonal and lacustrine); ii) the Lower Red Unit (fluvial and floodplain); iii) the Vallcebre limestones and lateral equivalents (lacustrine) and iv) the Upper Red Unit (palustrine, alluvial and fluvial). This subdivision has been extensively used in recent years. Finally, López-Martínez *et al.* (2001, 2006) reviewed several sections from the Tremp and Àger basins, including the Fontllonga section. These authors renamed the units of the Fontllonga section as Unit 1 to Unit 4. However their purpose was to describe in detail the Unit

TABLE 1. Equivalences in the nomenclature of the Upper Cretaceous continental deposits of the Àger Basin

Colombo and Cuevas (1993)		López-Martínez *et al.* (2001)	Rosell *et al.* (2001)
Fontllonga Group	Perauba Complex	Unit 4	Upper Red Unit
	Millà Formation	Unit 3	Vallcebre limestone and lateral equivalents
	Figuerola Formation	Unit 2	Lower Red Unit
	La Maçana Formation	Unit 1	Grey Unit

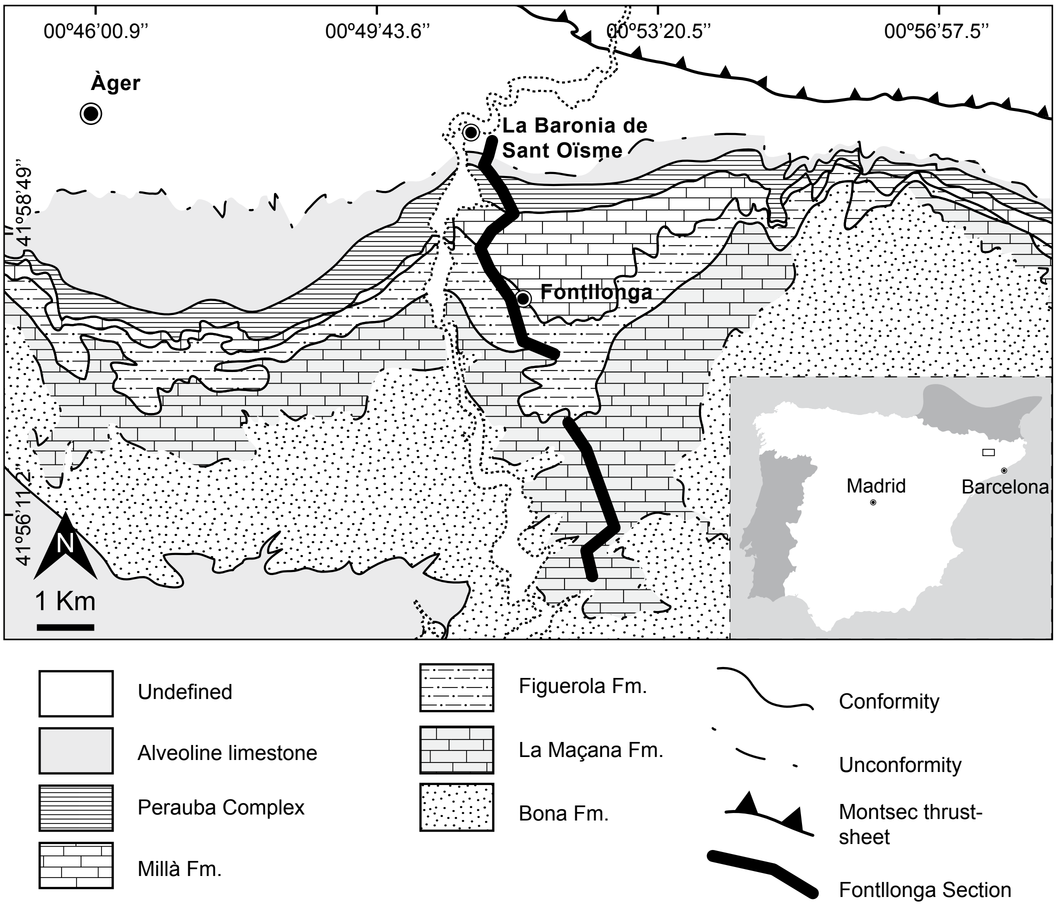

FIGURE 1. Geological setting of the Àger Basin with the location of the Fontllonga section (modified from: Institut Cartogràfic de Catalunya, 2006).

3 equivalent to the Millà Fm. (Vallcebre limestone), which was interpreted as a succession of calcimorf palaeosoils formed in freshwater lake margins.

MATERIAL AND METHODS

In order to characterise the sedimentology and palaeoecology of the non-marine Upper Cretaceous–Palaeocene deposits in the Àger Basin, a composite stratigraphic section was logged along the road C-13 (Fig. 1). This road shows a fine exposure of the continental section, from its base at the house called Cal Magí (41º 55' 24.92"N, 00º 52' 23.37"E) to the top in the proximity of the village of La Baronia de Sant Oïsme (41º 59' 37.7"N, 00º 50' 48.2"E). A systematic sampling of the sections was carried out, focusing on the greyish marls, and 47 new samples were selected for detailed study. Additionally, 26 samples from La Maçana Fm. were analysed in a previous study by Villalba-Breva and Martín-Closas (2013). Charophyte fructifications (gyrogonites and utricles) were obtained after disaggregating a normalised weight (3kg) of sediment in a hydrogen peroxide and water solution. After screen-washing the sediment with sieves of mesh sizes of 200, 500 and 1000μm, the fructifications were selected by hand using a Wild M5A binocular microscope. Representative samples of mainly index species of charophyte biozones were photographed using a Quanta 200 scanning electron microscope at the "Centres Científics i Tecnològics" of the University of Barcelona. Foraminifers were studied in thin section and photographed with a digital camera Zeiss AxioCam MRc 5 mounted on a petrographic microscope Zeiss Axioplan 2. The material is housed partly in the Departament de Dinàmica de la Terra i de l'Oceà (previously Dept. d'Estratigrafia, Paleontologia i Geociències Marines) of the University of Barcelona and partly in the Museu de Geologia del Seminari Conciliar de Barcelona (MGSCB).

STRATIGRAPHY, SEDIMENTOLOGY AND BIOSTRATIGRAPHY

The stratigraphic data provided here follow the litostratigraphic nomenclature of Colombo and Cuevas (1993) and Rosell *et al.* (2001). The combined

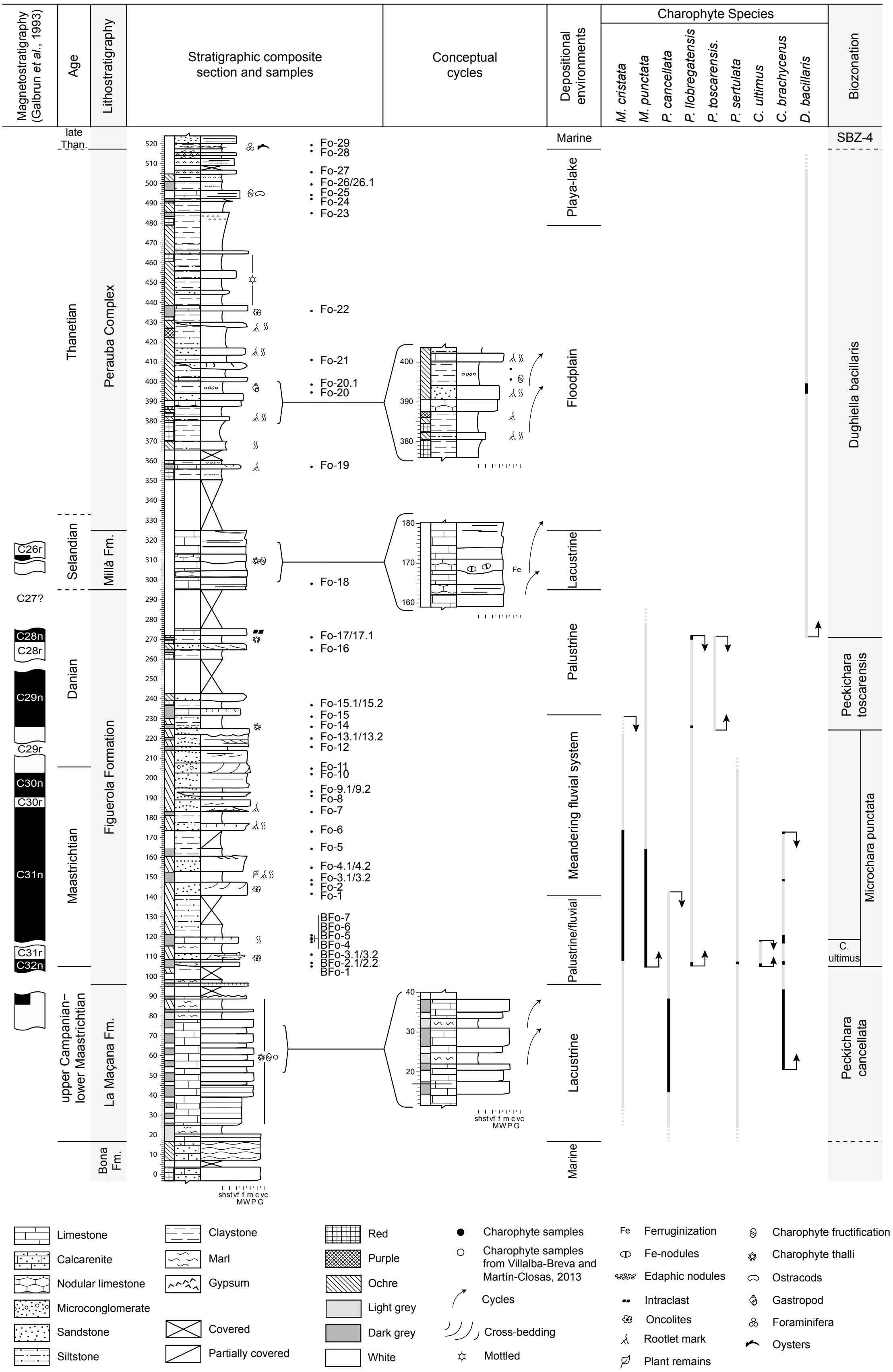

FIGURE 2. The composite Fontllonga stratigraphic section including the conceptual cycles, distribution of the facies and charophyte biozonation for the Àger Basin. Chronostratigraphic data from Galbrun *et al.* (1993).

sedimentological and taphonomic analyses presented herein are a necessary premise to propose an improved European charophyte biozonation for the late Cretaceous to early Palaeogene in the reference section of Fontllonga.

La Maçana Formation

Stratigraphy and Sedimentology

Situated alongside C-13 road, between Cal Magí and the junction with the road to Fontllonga village, La Maçana Fm. includes up to 100m of charophyte-rich limestone beds with characteristic white and dark grey bands, alternating sporadically with light grey marls towards the top. Villalba-Breva and Martín-Closas (2013) analysed the microfacies and the biostratigraphy of this unit that is formed of hundreds of cycles, of few decimetres to almost three metres thick. The same authors interpreted these cycles as small-scale shallowing-upward lacustrine cycles, probably climatically driven (Fig. 2).

Charophyte assemblages and biostratigraphy

After taphonomic analysis, the charophyte assemblages from the different parts of the described cycles were attributed by Villalba-Breva and Martín-Closas (2013) to different lacustrine belts. They observed that assemblages of relatively deeper lake conditions were dominated by the genera *Peckichara* and *Microchara*, and those corresponding to shallow lake margins were dominated by *Clavator*/*Munieria* assemblages. The charophyte fructifications found in the marls are composed mainly of *Peckichara cancellata* Grambast, 1971; *P. sertulata* Grambast, 1971; *Microchara parazensis* Massieux, 1987 in Massieux *et al.*, 1987; *Platychara caudata* Grambast, 1971 and *Clavator brachycerus* (Grambast, 1962) Martín-Closas, 1996 (=*Septorella brachycera* Grambast). Some species, such as *Feistiella malladae* (Bataller, 1945) Villalba-Breva and Martín-Closas in Villalba-Breva *et al.*, 2012, *Microchara cristata* Grambast, 1971, *Dughiella obtusa* Grambast and Gutiérrez, 1977 and *Platychara turbinata* Grambast and Gutiérrez, 1977, occur in smaller proportions (Figs. 3; 4).

The charophyte assemblage found in La Maçana Fm. was placed by Villalba-Breva and Martín-Closas (2013) within the Peckichara cancellata biozone (Upper Campanian–basal Maastrichtian), calibrated from chron (C33?) C32r to chron C31r according to Riveline *et al.* (1996) and Vicente *et al.* (2015). However, the exact age of this formation is controversial. According to Galbrun *et al.* (1993), the upper boundary of La Maçana Fm. still belongs to the Campanian (chron C32r). In contrast, Caus *et al.* (2016) recently attributed the underlying marine limestones of Bona Fm. to the lower Maastrichtian, based on strontium isotope data combined with larger benthic foraminifera and rudist biostratigraphy.

Lower part of the Figuerola Formation

Stratigraphy and Sedimentology

Above La Maçana Fm. and following the road C-13 northwards, the 400m thick Figuerola Fm. is built up of reddish claystones, limestone beds and abundant channelled sandstones. The lower part of this formation is composed by a 25m thick alternation of reddish claystones with abundant fine-grained sandstone channels, with cross-bedded stratification, sometimes rich in oncolites. Sporadically, highly bioturbated limestones and marls occur. Claystones are organised in cycles, 1-2m thick, with grey claystones at the base, ochre claystones in the middle part and red claystones at top. Topping the cycles there are the channelled sandstones.

These cycles have been attributed to floodplain facies subjected to edaphic processes, that changed from ephemeral ponds (grey claystones) at the base, to well-drained and long exposed facies at the top of the cycle (red claystones). The grey marls and bioturbated limestone are organised in small cycles that represent shallowing upward lacustrine sequences.

Charophyte assemblages and biostratigraphy

The limestone beds contain abundant charophyte thalli (*Munieria grambastii* Bystrický, 1976; attributed to clavatoracean axes, *Charaxis* and *Clavatoraxis*) and charophyte fructifications. Charophyte assemblages are mainly found in grey marls and are composed of *Microchara cristata*; *Microchara punctata* Feist and Colombo, 1983; *Microchara nana* Vicente and Martín-Closas, 2015 (in Vicente *et al.*, 2015); *Peckichara sertulata*; *Peckichara llobregatensis* Feist and Colombo, 1983; *Platychara* sp., *D. obtusa*; *Clavator ultimus* (Grambast, 1971) and *C. brachycerus* (Figs. 3; 4). Most of the charophyte gyrogonites of these assemblages are well-preserved suggesting autochthony to parautochthony in the floodplain ponds. However, *C. brachycerus* and *C. ultimus* generally form assemblages of well-preserved utricles associated with specimens showing mechanical fracturing which results in the exposure of the internal nodular layer. These specimens would indicate significant lateral transport within the floodplain, and allochtony. The assemblages of *C. ultimus* were found in facies corresponding to very shallow ponds with high terrigenic influence, usually associated to fluvial systems. In such a facies the co-occurrence of autochthonous and allochthonous specimens can be easily understood.

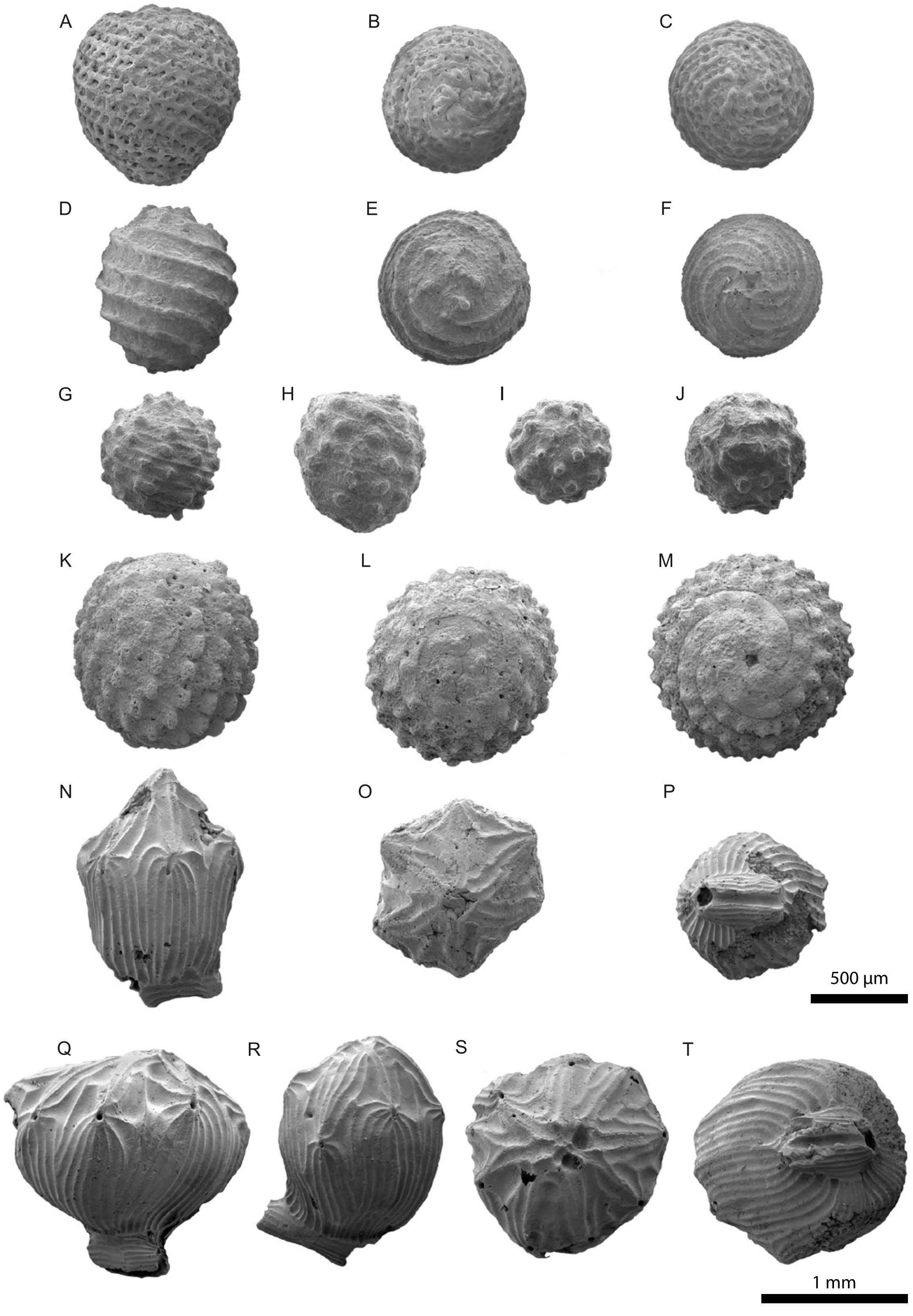

FIGURE 3. Selected charophyte fructifications from the Fontllonga section significant for charophyte biostratigraphy. A-C) *Peckichara cancellata*, samples from MAÇ-2, La Maçana section (Villalba-Breva and Martín-Closas, 2013); A) lateral view, B) apical view and C) basal view. Specimens 82583 to 82585 of MGSCB. D-F) *Peckichara sertulata*, samples from ALZ-2, Alzina-Beniure section (Villalba-Breva and Martín-Closas, 2013); D) lateral view, E) apical view and F) basal view. Specimens 82586 to 82588 of MGSCB. G-J) *Peckichara llobregatensis*, G-H) samples from BFo-1 and I-J) samples from Fo-17, Fontllonga section. G-H) lateral view, I) apical view and J) basal view. Specimens 82589 to 82592 of MGSCB. K-M) *Dughiella bacillaris*, samples from Fo-20, Fontllonga section; K) lateral view, L) apical view and M) basal view. Specimens 82593 to 82595 of MGSCB. N-P) *Clavator brachycerus*, sample BFo-4, Fontllonga section; N) lateral view, O) apical view and P) basal view. Specimens 82596 to 82598 of MGSCB. Q-T) *Clavator ultimus*, Q-S-T) samples from BFo-2.2, R) sample from BFo-5, Fontllonga section. Q-R) lateral views, S) apical view and T) basal view. Specimens 82599 to 82602 of MGSCB.

The charophyte assemblages found in the lower part of the Figuerola Fm. largely coincide with the charophyte assemblages that Galbrun *et al.* (1993) found at the same levels and attributed to the Middle Microchara cristata zone, later renamed Septorella ultima biozone by Riveline *et al.* (1996). This biozone is relegated here to a subzone (the Clavator ultimus subzone) within the more comprehensive Microchara punctata biozone described by Vicente *et al.* (2015). The reason for this change is that the index species of this subzone, *C. ultimus*, is extremely limited to facies attributed to fluvial ponds that occur only rarely within the basin. In contrast, Microchara punctata has been widely recognised in a broad range of environments ranging from lacustrine to floodplain facies. Riveline *et al.* (1996) calibrated the Septorella ultima biozone (Clavator ultimus subzone) with the upper boundary of chron C32n and chron C31n based on the magnetostratigraphic data from the Fontllonga section provided by Galbrun *et al.* (1993).

Middle part of the Figuerola Formation

Stratigraphy and Sedimentology

Following the road C-13, between the kilometric points 60 and 61 a coarse terrigenic unit crops out. In this part, the Figuerola Fm. shows a succession of tabular and channelled coarse sandstone beds (2–3m thick) with cross-bedded stratification. Some channel bodies show lateral accretion structures and display highly bioturbated top surfaces. The channels alternate with poorly developed variegated claystone beds. The upper part of the succession is formed by the so-called Reptile Sandstones (Masriera and Ullastre, 1982), composed of a 40m thick succession of coarse sandstone or even microconglomerate channels.

This unit has been interpreted as a vertical evolution from fluvial floodplain facies to well-drained fluvial system with large meandering river channels at the top. According to some authors these channels may show tidal influence (López-Martínez *et al.*, 2006).

Charophyte assemblages and biostratigraphy

Charophyte assemblages (Figs. 3;. 4) are mainly found in the grey marls and claystones at the base and are composed of *Microchara cristata*, *M. punctata*, *M. nana*, *Peckichara llobregatensis*, *Platychara* sp., *Lychnothamnus begudianus* (Grambast, 1962) Soulié-Märsche, 1989 and *C. brachycerus*. Thalli of *Clavatoraxis* and *Munieria grambastii* were also found. The charophyte assemblages show well preserved gyrogonites indicating autochthony or parautochthony in small temporary floodplain ponds. The gyrogonites of this facies are generally small sized and belong to genus *Microchara*.

The charophyte assemblage have been assigned to the Microchara punctata biozone of Vicente *et al.* (2015). This part of the Figuerola Fm. was included by Galbrun *et al.* (1993) in the lower-upper Microchara cristata and upper-upper Microchara cristata zones. Later these biozones were renamed Microchara cristata and Peckichara sp. 1 zones by Riveline *et al.* (1996); both of them being poorly characterized as explained in Vicente *et al.* (2015). The K/Pg boundary has been located in the upper part of the Reptile Sandstones, in a claystone bed between fluvial sandstones, broadly identified by means of magnetostratigraphic data (Galbrun *et al.*, 1993) and later refined by López-Martínez *et al.* (2001).

Upper part of the Figuerola Formation

Stratigraphy and Sedimentology

The upper part of Figuerola Fm. above the Reptile Sandstones consists of a marly and lutitic succession with intercalations of nodulose lacustrine limestones and sandstone channels with abundant oncolites. These facies are organised in deepening upward cycles (~5m thick) with reddish claystones and sandstone channels at the base, passing upward to grey marls and finally lacustrine limestones, indicating the abandonment of the fluvial system and the establishment of small ponds and lakes.

Charophyte assemblages and biostratigraphy

The grey marls above the Reptile Sandstones contain charophyte assemblages mainly composed of *Peckichara llobregatensis*, *Microchara nana*, *Lychnothamnus* sp. and *Platychara* sp. According to Galbrun *et al.* (1993), these beds also contain *Maedleriella* aff. *michelina* Märsche, 1969, *Nitellopsis* aff. *helicteres* (Brongniart, 1822) Grambast and Soulié-Märsche, 1972, *Peckichara toscarensis* Feist and Colombo, 1983, *Dughiella wanghuangensis* Huang, 1988 and *Sphaerochara edda* Soulié-Märsche, 1971. Later, Mayr *et al.* (1999) found a similar charophyte assemblage *Dughiella bacillaris*, *P.* cf. *toscarensis*, *N.* aff. *helicteres*, *S. edda* among others, but with the addition of *Microchara punctuata* Riveline, 1986. The latter gyrogonites are re-assigned here to *M. punctata* given the strong similarities of the material figured by Mayr *et al.* (1999, Plate 2) with this species. Indeed, gyrogonites of *M. punctata* differ from *M. punctuata* of the lower Sparnacian (basal Ypresian) deposits of the Paris Basin mainly in the regular distribution of the tubercular ornamentation and in its more elongated shape. The assemblage shows well preserved gyrogonites suggesting that they were autochthonous in the environment mentioned above, *i.e.* in small lakes or ponds occurring in the context of a palustrine environment.

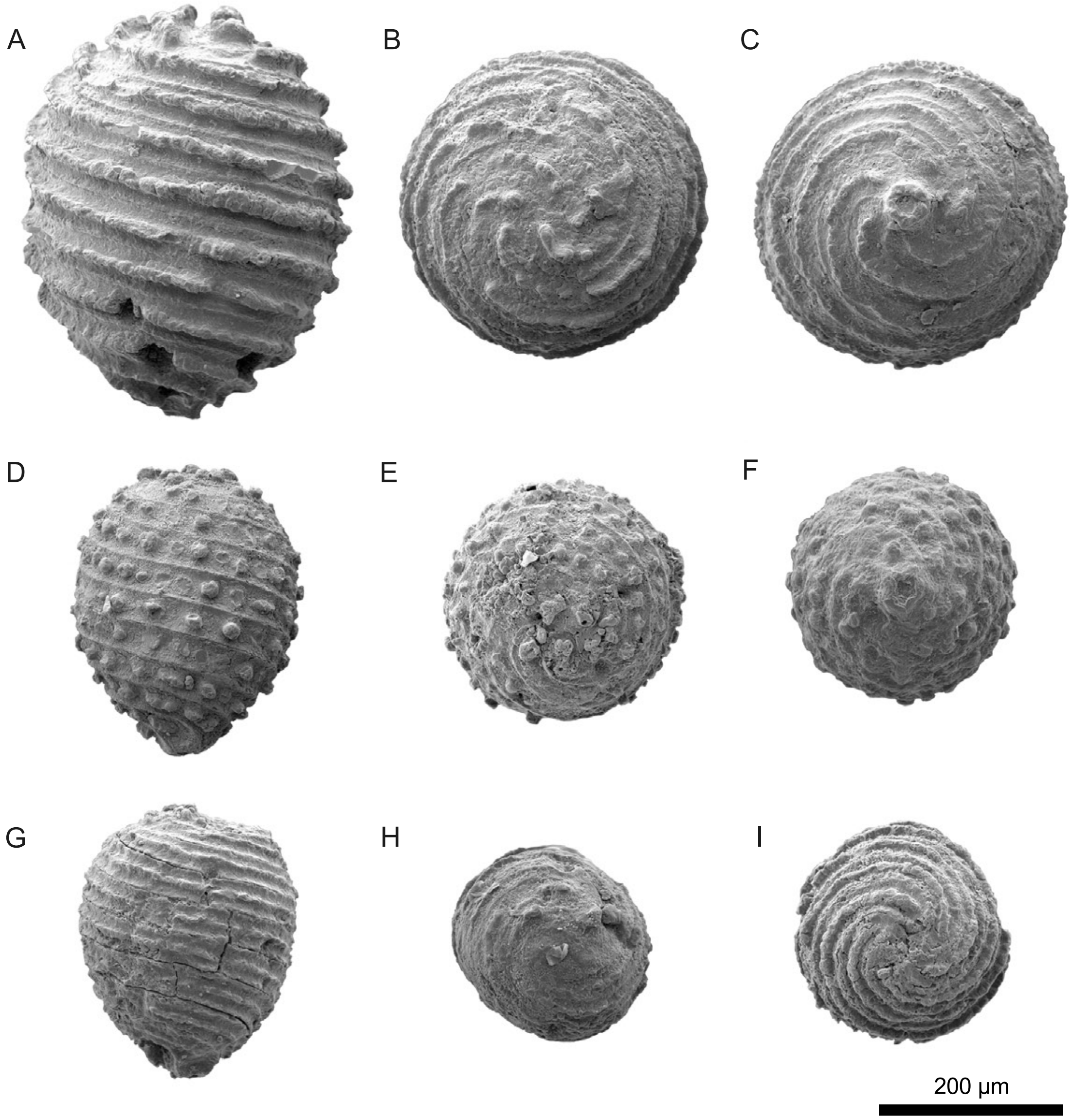

FIGURE 4. Selected charophyte fructifications from the Fontllonga section significant for charophyte biostratigraphy. A-C) *Microchara cristata*, samples from Fo-5, Fontllonga section; A) lateral view, B) apical view and C) basal view. Specimens 82603 to 82605 of MGSCB. D-F) *Microchara punctata*, samples from Bfo-1, Fontllonga section; D) lateral view, E) apical view and F) basal view. Specimens 82606 to 82608 of MGSCB. G-I) *Microchara nana*, samples from BFo-1, Fontllonga section; G) lateral view, H) apical view and I) basal view. Specimens 82609 to 82611 of MGSCB.

The assemblage of this part of the Figuerola Fm. is assigned to the Peckichara toscarensis biozone of Galbrun *et al*. (1993) attributed to the lower Danian. This biozone was later on renamed Peckichara llobregatensis zone (Riveline *et al*., 1996). However, Vicente *et al*. (2015) found that the latter index species already occurred in the Maastrichtian, and thus its first occurrence datum was inappropriate to characterise the lower Danian. In the upper part of Figuerola Fm., about 20m below the top of the formation., Galbrun *et al*. (1993) and Mayr *et al*. (1999) reported the first occurrence of *D. bacillaris*, marking the beginning of the Dughiella bacillaris biozone, upper Danian (informally called "Dano-Montian") to early Thanetian in age (Riveline *et al*., 1996).

Millà Formation

Stratigraphy and Sedimentology

Considered a lateral equivalent of the Vallcebre limestones (Vallcebre Basin) in the Àger Basin, this unit was studied in detail from the stratigraphic and sedimentological viewpoint by López-Martínez *et al*. (2006). In the Fontllonga section, the Millà Fm. consists of over 30m of lacustrine and palustrine limestones, internally organised in cycles of 2–4m, starting with nodulose limestones (pseudo-microkarst) with irregular bases that gradually change upward to white, massive and marmorised limestones with charophyte thalli and gyrogonites. The top of the formation shows abundant lamination and fenestral porosity, probably of algal origin. These cycles are interpreted here as deepening upward lacustrine sequences, ending abruptly with a period of water starvation and the eventual exposure of the lake.

Charophyte assemblages and biostratigraphy

The absence of marly beds prevented the identification charophyte assemblages that would be useful to characterise the formation biostratigraphically. However, the limestones of Millà Fm. were calibrated magnetostratigraphically by Galbrun *et al*. (1993) with chron C26r (late Danian to Selandian).

Perauba Complex

Stratigraphy and Sedimentology

This unit is poorly exposed along the road C-13, it was studied on the northern slope of the neighbouring Torrent de Canemars ravine, *i.e*. the southern slope of the hill called L'Altera. The unit is 135m thick, its lower part being composed of cycles, some 10m thick, of reddish, ochre or variegated claystones at the base, passing upward to very fine-grained tabular sandstones with abundant bioturbation and rootlet marks. Some sporadic calcarenitic layers or highly bioturbated and nodulose limestone beds with "*Microcodium*" occur at the top of the cycles. This part of the Fontllonga section is attributed to sedimentation in a fluvial floodplain that underwent periodical inundation.

The upper part of Perauba Complex (approximately 30m thick) was studied along the road C-13, 1–2km south of the village of La Baronia de Sant Oïsme. This part of the unit is composed of alternating limestones, marls and massive, nodulose and laminated gypsum beds. These beds were interpreted by Colombo and Cuevas (1993) as playa-lake deposits formed in the distal area of the floodplain. Marine levels formed by marls and limestones with abundant miliolids and some oyster beds occur above the evaporitic sequences.

Charophyte assemblages and biostratigraphy

Charophytes from Perauba Complex were unknown to date (Fig. 3). The most significant assemblage for biostratigraphy was in a bed found in the lower part of the complex, in the ochre floodplain claystones. This bed occurs at the basal part of one of the sedimentary cycles, which is topped by a thin, highly bioturbated limestone layer.

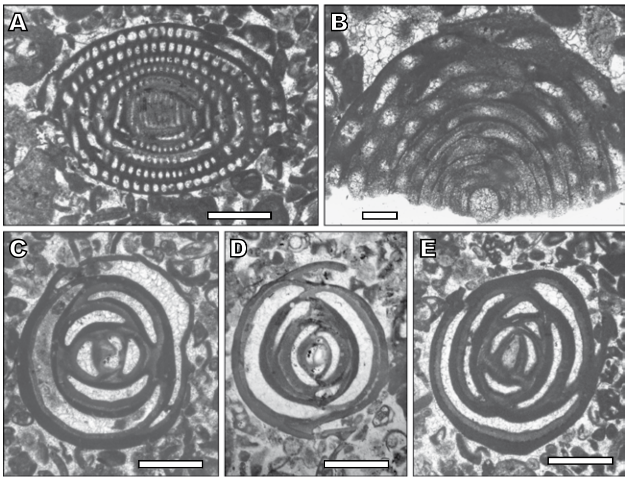

FIGURE 5. Benthic foraminifera found in the first marine beds of the Fontllonga section. A-B), *Glomalveolina levis*; C-E), *Idalina sinjarica*. Samples A and E from 34283 of MGSCB. Sample B from 34284 of MGSCB. Sample C from 34285 of MGSCB. Sample D from 34286 of MGSCB. White scale bars: 500µm; black scale bar: 100µm.

The assemblage is composed of *D. bacillaris* (Fig. 3K–M), *Microchara* sp. and *Harrisichara* sp., (sample Fo-20; Fig. 2). This bed is particularly rich in charophyte remains and the gyrogonites are well preserved, suggesting that the assemblage is autochthonous. These charophytes probably grew in small ponds formed in the floodplain after flood events. This assemblage belongs to the Dughiella bacillaris biozone, ranging from the upper Danian to basal Thanetian (Riveline *et al*., 1996). The remainder of the non-marine succession provided only a few gyrogonites of *Microchara* sp. The first marine beds overlying the playa-lake deposits are rich in miliolids and yield a biostratigraphically significant assemblage formed by rare *Glomalveolina levis* HOTTINGER, 1960 and *Idalina sinjarica* GRIMSDALE, 1952, which represent the Shallow Benthic Zone (SBZ) 4, indicating a late Thanetian age (Fig. 5) (Serra-Kiel *et al*., 1998; Scheibner and Speijer, 2009).

CHAROPHYTE BIOZONATION

The new data obtained from the continental Upper Cretaceous–Palaeocene deposits of the Fontllonga section allows refining the local biozonation proposed by Vicente *et al*. (2015) in the Vallcebre Basin and puts forward a new charophyte biozonation for the south Pyrenean basins (Fig. 6).

Peckichara cancellata biozone

This is a partial-range zone defined by the first occurrence of *P. cancellata* and ending with the first occurrence of *M.*

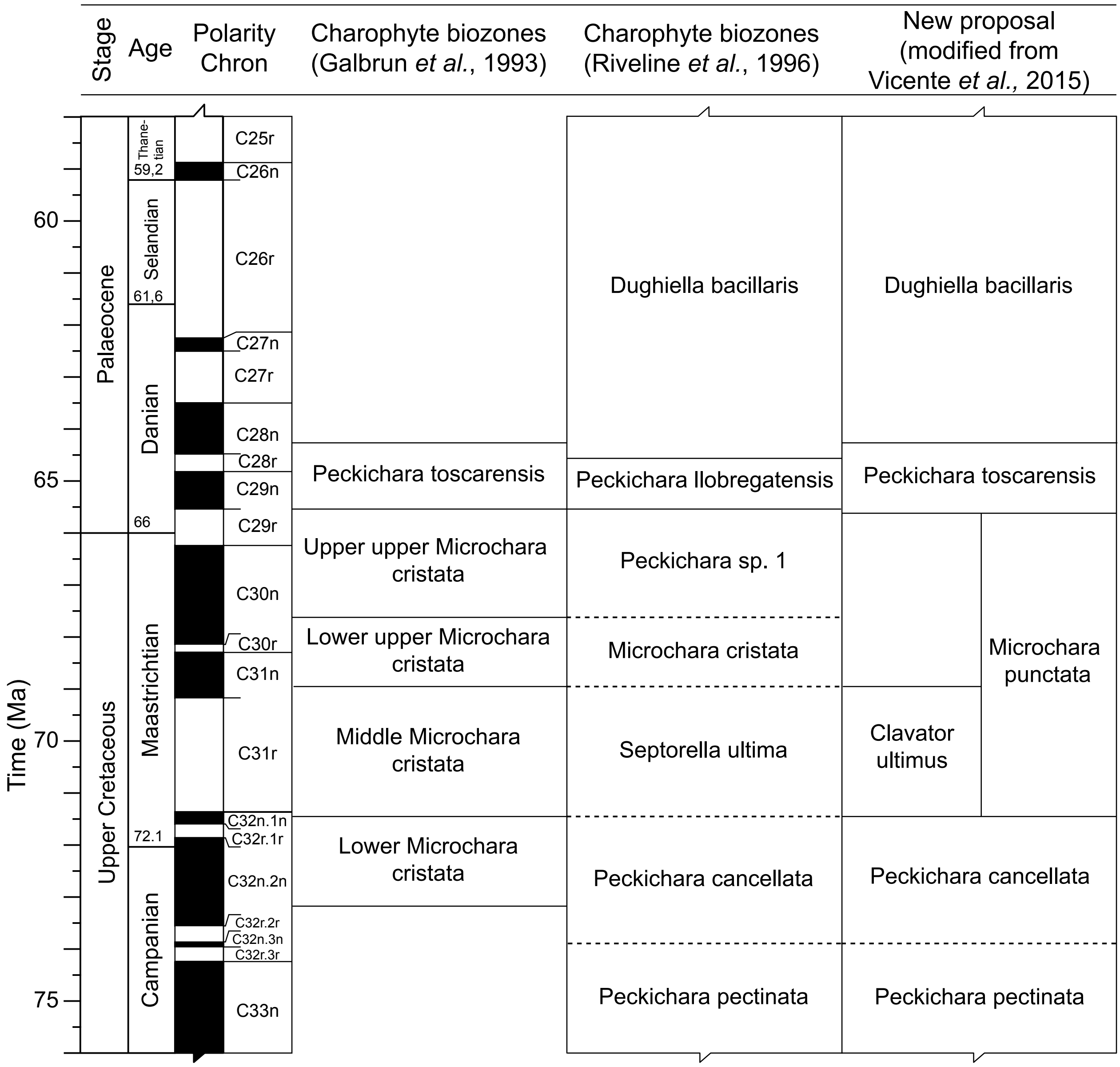

FIGURE 6. New Late Cretaceous Palaeocene charophyte biozonation of the Fontllonga section modified from Vicente *et al.* (2015), and a comparison with the biozonations proposed by Galbrun *et al.* (1993) and Riveline *et al.* (1996).

punctata. The upper boundary of the *P. cancellata* biozone was calibrated with chron C31r in the Vallcebre Basin (Vicente *et al.*, 2015). However, the ocurrence of *M. punctata* in the upper part of chron C32n.1n in the Fontllonga section leads lowering this boundary accordingly. The charophyte assemblage of this biozone in the southern Pyrenean basins comprises: *P. sertulata*, *M. cristata*, *M. nana* and *C. brachycerus* along with the index species *P. cancellata*.

Microchara punctata biozone

This is a partial-range biozone comprising the interval between the first appearance of *M. punctata* and the first appearance of *P. toscarensis*. The base of this biozone has been calibrated to the chron C32n.1n. The attribution of the specimens previously described by Mayr *et al.* (1999) as *M. punctuata* to the index species (*M. punctata*) results in a modification of the Microchara punctata zone described by Vicente *et al.* (2015) by extending the upper boundary to the first appearance of *P. toscarensis* in chron C29r, indicating an age of ~65.62Ma (earliest Danian). The report of *M. punctata* in Danian deposits of the Fontllonga section enables resolving the "undefined interval" reported by Vicente *et al.* (2015) in the upper Maastrichtian–lowermost Danian charophyte biozonation. The index species has usually been found with *P. sertulata*, *M. cristata*, *M. nana*, *C. brachycerus* and *C. ultimus*.

A total-range Clavator ultimus subzone has been described in the lower part of the Microchara punctata zone to characterise the lower and middle Maastrichtian deposits. This subzone corresponds to the total-range Septorella ultima zone defined by Riveline *et al.* (1996) and was calibrated with chron C32n to C31n (lower Maastrichtian). *C. ultimus* has usually been found with *P. sertulata*, *M. cristata* and *C. brachycerus* in the south Pyrenean basins.

Peckichara toscarensis biozone

This represents a partial-range zone defined between the first occurrence of *P. toscarensis* and the first occurrence of *Dughiella bacillaris*. The base of this biozone was calibrated with the upper part of chron C29r in the Vallcebre Basin (Vicente el al., 2015) and the upper boundary in the base of chron C28n according to Galbrun *et al.* (1993). The index species is associated with *P. llobregatensis* (large morphotype), *M. cristata*, *M. nana*, *N.* aff. *helicteres*, *S. edda* and *Lychnothamnus* sp.

Dughiella bacillaris biozone

This is a total-range biozone described by Riveline *et al.* (1996) to characterise the range from the upper Danian to lower Thanetian. According to Galbrun *et al.* (1993), the first report of the type species *D. bacillaris* was calibrated with the basal part of chron C28n. However, Riveline *et al.* (1996) reported this species already in the Peckichara llobregatensis biozone (equivalent to the P. toscarensis biozone) within chrons C29n and C28r. In the Fontllonga section this index species is associated with *M. michelina*, *N.* aff. *helicteres*, *P. llobregatensis*, *P. toscarensis*, *P. varians*, *S. edda* and others (Galbrun *et al.*, 1993; Mayr *et al.*, 1999)

DISCUSSION

Feist in Riveline *et al.* (1996) used the preliminary charophyte biozonation proposed by Galbrun *et al.* (1993) with data from the Fontllonga section, Àger Basin, to describe a total of five European biozones for the Maastrichtian and early Danian continental deposits, *i.e.* the Peckichara cancellata zone, Septorella ultima zone, Microchara cristata zone, Peckichara sp. 1 zone and Peckichara llobregatensis zone (Fig. 6). This biozonation has been recently revisited by Vicente *et al.* (2015) in order to resolve a number of inconsistencies, such as the use of interval zones, lack of taxonomic precision of one index species and lack of palaeoecological data of all index species. These authors pointed out that a regional charophyte biozonation should be based on a compilation of local biozonations, because of the biogeographic limitation of some index species and the differences in facies between basins, which might influence the composition of the charophyte assemblages.

New stratigraphic, sedimentological, taphonomic and palaeoecological analyses have been carried out in the Fontllonga reference section. In comparison with the biozonation proposed for the Vallcebre Basin (Vicente *et al.*, 2015), some modifications are introduced. The basal boundary of the Microchara punctata biozone is extended from the middle-upper part of chron C31r to reach the base of chron C31r, due to the occurrence of the index species in the lower interval of Figuerola Fm. To improve the characterisation of the Microchara punctata biozone, a new zone, the Clavator ultimus subzone, is introduced. This subzone corresponds to the total-range of the Septorella ultima biozone of the European biozonation proposed by Riveline *et al.* (1996), which is relegated here to the subzone rank due to the facies restriction of its index species. Finally, the top of the Microchara punctata biozone is extended from the middle part of chron C30n to reach chron C29r and the first appearance datum of *P. toscarensis*. This has been possible after reassignation of the gyrogonites described by Mayr *et al.* (1999) as *M. punctuata* to the species *M. punctata* in the upper part of the Figuerola Fomation (lower Danian). This allowed resolving the "undefined interval" (uppermost part of the Maastrichtian) of the charophyte biozonation proposed by Vicente *et al.* (2015) in the Vallcebre Basin. Finally, the occurrence of *D. bacillaris* in the Perauba Complex, enabled assigning this unit to the homonymous biozone. The non-marine deposits of the Fontllonga section are topped by late Thanetian marine beds, as shown by the occurrence of benthic foraminifera belonging to the SBZ4 above the Perauba Complex gypsum beds.

CONCLUSIONS

The new data obtained from the Fontllonga section allows revision of the previous charophyte biostratigraphy of the non-marine Upper Cretaceous–Palaeocene deposits in the Àger Basin proposed by Galbrun *et al.* (1993) and Feist in Riveline *et al.* (1996). The charophyte distribution reported in the Fontllonga section also enables modification of the previous local biozonation proposed by Vicente *et al.* (2015) in the Vallcebre Basin (Fig. 6).

The biozonation proposed by Vicente *et al.* (2015) for the Vallcebre Basin has been successfully applied to the Fontllonga section, which suggests that it can be used at a regional scale. The new proposal contains four biozones which take into account the charophyte taxonomy, taphonomy and charophyte palaeoecology. From base to top the four biozones proposed are the Peckichara cancellata biozone, Microchara punctata biozone including the Clavator ultimus subzone, Peckichara toscarensis biozone and the Dughiella bacillaris biozone. This new proposal intends to provide a new biozonation that is applicable to the whole Ibero-armorican realm and useful to establish future European and Euroasiatic charophyte biozonations.

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