Maastrichtian-lower Paleocene charophyte biozonation and its calibration to the Global Polarity Time Scale in the Southern Pyrenees (Catalonia, Spain).

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ABSTRACT

A new charophyte biozonation for the non-marine Maastrichtian–lower Paleocene deposits in the South-Eastern Pyrenean Vallcebre Basin is proposed and calibrated to the Global Polarity Time Scale (GPTS) with magnetostratigraphic data. Planktonic foraminifera associated with charophyte assemblages provide minimum ages for correlation between non-marine and marine biostratigraphic zonations. The new charophyte biozonation is intended to be useful for terrigenous floodplain facies (red beds) with poorly developed lacustrine intervals and strong palaeoecological constraints for the development of charophytes. To reach this purpose the taxonomy of charophytes has been revisited and two new species were defined, *Microchara nana* Vicente and Martín-Closas and *Peckichara serrata* Vicente and Martín-Closas. Sedimentological analyses carried out in parallel with taphonomic observations allow us to infer the palaeoecological constrains of charophyte species. The new biozonation encompasses three biozones for the late Campanian–early Paleocene interval. The Peckichara cancellata partial range biozone starts in chron C32r (~ 73.26 Ma) according to previous studies and has its upper limit enlarged to chron C31r, with an age of ~ 69,36 Ma in the Vallcebre Basin. The new Microchara punctata local biozone includes previous biozones of Septorella ultima (upper part), Microchara cristata and Peckichara sp. 1 (lower part) defined by Riveline et al. (1996). Some of these biozones were poorly defined or were based on species with strong palaeoecological constraints. The lower Danian is characterized with the biozone of Peckichara toscarensis in substitution of previous biozone of Peckichara llobregatensis, based on a species that was found to occur already in the Maastrichtian.

Keywords: Charophyta; Planktonic foraminifera; Biostratigraphy; Magnetostratigraphy; Late Cretaceous; Spain.

1. Introduction

Calcified charophyte fructifications (gyrogonites and utricles) are well preserved in the fossil record of non-marine deposits since the Silurian (Feist et al., 2005) and their relatively high evolutionary rates make them an appropriate biostratigraphic tool in non-marine deposits. Particularly, the charophytes of the Upper Cretaceous and Paleocene deposits of Europe were long studied to characterize the Cretaceous/Paleogene (K/Pg) boundary. After the pioneering biostratigraphic studies of Grambast (1962, 1964) and Massieux et al. (1979) in southern France, intensive work was carried out in the southern Pyrenees to establish a formal charophyte biozonation. The first biostratigraphic studies by Feist and Colombo (1983) and Médus et al. (1988) were followed by the proposal of a first local biozonation that was calibrated to the GPTS with palaeomagnetic data by Galbrun et al (1993) in the Fontllonga section, Àger Basin (Serres Marginals thrust sheet). This section was considered later as a reference section for charophyte biostratigraphy and the results obtained there were of crucial interest to elaborate the first consensus charophyte biozonation for the Upper Cretaceous–lower Paleogene at the European scale by Feist in Riveline et al. (1996) and Feist in Hardenbol et al. (1998). Five charophyte biozones, Peckichara cancellata, Septorella ultima, Microchara cristata, Peckichara sp. 1 and Peckichara llobregatensis Biozones, were proposed to characterize the Maastrichtian and early Danian. Since then, this biozonation has been poorly used and most of the biostratigraphic studies were based directly on the assemblage of particular charophyte species (Mayr et al, 1999; López-Martínez et al., 2001). The Upper Cretaceous charophyte biozonation proposed by Riveline et al (1996) needs to be improved in a number of points. First, the S. ultima Biozone has a poorly known biostratigraphic range due to the discontinuous occurrence and unknown palaeoecological requirements of the index species. Other biozones remain poorly defined, such as the M. cristata zone, identified solely by the first and last appearances of species from overlying and underlying zones respectively or the Peckichara sp. 1 zone, which is obviously lacking taxonomic precision.

Here we present a new local biozonation for the Pyrenean Upper Cretaceous, that combines the results from Galbrun et al. (1993) in the Fontllonga section (Àger Basin , Central South Pyrenees), with own results in the Vallcebre Basin (Eastern Pyrenees) taking into account previous data from this basin by Feist and Colombo (1983) and Médus et al. (1988). The new proposal intends to solve the weak-points of the biozonation proposed by Riveline et al. (1996) for the Upper Cretaceous. Our data were obtained in the same sections and beds that were characterised magnetostratigraphically by Oms et al (2007), which allow us to calibrate the new proposal to the GPTS. Some samples supplied abundant planktonic foraminifera, providing additional information about minimum ages. The new biozonation takes into account the palaeoecological constraints of charophyte species, shedding light on the use of charophyte biozones in non-lacustrine environments, such as floodplains, which are very common in the continental Upper Cretaceous of Eurasia and North America.

2. Material and Methods

Three sections of the Upper Cretaceous of the Vallcebre Basin, Pedraforca thrust sheet - Eastern Pyrenees, were sampled systematically (Fig. 1B) to identify the charophyte assemblages of the Lower Red Unit. These sections are Mina Tumí (42º 12' 3.64" N, 1º 47' 22.17"E base and 42º 12' 12.91"N, 1º 47' 13.26"E top coordinates), Coll de Pradell (42º 12' 11.06"N, 1º 46' 13.56"E base and 42º 12' 19.12"N, 1º 46' 14.99"E top coordinates) and Cal Borni (42º 12' 6.53"N, 1º 48' 17.00"E base and 42º 12' 8.10"N, 1º 48’ 17.73"E top coordinates). These three sections were correlated to each other and with the Fumanya Sud section, previously studied by Villalba-Breva and Martín-Closas (2011).

Gyrogonites and utricles were obtained disaggregating a normalized weight of 3 kg of variegated claystones and siltstones in a solution of water and hydroxide peroxide (H_2O_2). To deflocculate the clay, in some cases sodium carbonate was added. The sieves used during the process had mesh sizes of 1, 0.5 and 0.2 mm. To eliminate the possibility of contamination, the sieves were cleaned, dried and submerged in methylene blue before each sample washing. Hand-picking of the fructifications was done with a binocular stereo microscope Wild M5A. Specimens were cleaned using EDTA (6%) to eliminate the residual particles or cleaned with ultra-sounds. Thin sections of limestone bed have been prepared for microfacies analyses and studied with a microscope Motic BA310. These sections have a thickness of ca. 30 μm and were cut parallel and straight to the bedding surface. The disaggregated samples were quantitatively analysed to provide the relative abundance of charophytes through the section. About 100 charophyte gyrogonites and utricles obtained from non-consolidated samples were measured for biometric purposes with a Motic BA310 stereomicroscope with the help of Motic Images Plus 2.0 ML software. Selected fossil remains were photographed with a Quanta 200 Scanning electron microscope (SEM) at the Serveis Cientificotècnics of the University of Barcelona. The material is housed in the collections of the Departament d'Estratigrafia, Paleontologia i Geociències marines (University of Barcelona) except for the type material, which is stored in the Museu de Geologia del Seminari Conciliar de Barcelona.

For planktonic foraminifera studies, the samples were disaggregated in water with diluted H_2O_2 for 4 hours. The suspension was then washed through a 100–μm-mesh sieve and the > 100 μm fraction oven–dried at 50°C. The disaggregated samples were semi-quantitatively analysed to provide the relative abundance of planktonic foraminifera, which was recorded as abundant, common or rare. Representative specimens of all taxa were fixed to a standard 60-square micropaleontological slide to provide a permanent record. Some specimens were selected for scanning electron microscopy (SEM) analysis, using a JEOL JSM 6400 SEM at the Microscopy Service of the Universidad de Zaragoza (Spain). All residues, images and the chosen specimens themselves are stored at the Departamento de Ciencias de la Tierra of the Universidad de Zaragoza (Spain).

3. Geological Setting

The Pyrenees were formed due to the collision between the Iberian and European plates from the Campanian to the Oligocene. This collision resulted in the formation of an Alpine fold-thrust alongside east to west of northern Spain (Muñoz et al. 1986). The anticlockwise rotation of Iberia (Capote et al., 2002) and the oblique collision between both plates determined the first closing and continentalization of the South Pyrenean basin in the Late Cretaceous. The deposition during that period shows a general marine regression progressing from east to west (Mey et al., 1968; Rosell et al., 2001), with a south to north component (Villalba-Breva and Martín-Closas, 2013). As a result of thrusting, a number of small basins or depocenters were individualized in the South Pyrenean basin already during the Late Cretaceous and later included in Alpine thrust sheets forming strongly asimetrical synclines. These are, from East to West, Vallcebre, Coll de Nargó and Tremp-Graus basins, the latter bound to the South with the Àger Basin (Fig. 1A). The sections studied here are located in the Vallcebre Basin, within the allochtonous unit of the Lower Pedraforca thrust sheet (Muñoz et al., 1986; Puigdefàbregas et al., 1986).

-- Fig. 1 near here ---

The Upper Cretaceous–lower Paleocene non-marine clastic materials belong to the so-called "Garumnian" facies in classical regional studies (Leymerie et al., 1862). Later a number of formations were created to subdivide formally the Garumnian such as the Tremp Formation in the Tremp-Graus Basin (Mey et al., 1968). The Garumnian was also divided by Rossell et al. (2001), into four lithological units, which are from base to top the transitional marine to lacustrine Grey Unit, the fluvial Lower Red Unit, the lacustrine Vallcebre Limestone Formation and finally the fluvial Upper Red Unit. The K/Pg boundary was identified near the top of the Lower Red Unit (Rosell et al., 2001; Lopéz-Martínez et al., 2006; Oms et al., 2007). Above the Garumnian units the lower Eocene *Alveolina* limestone is the more conspicuous rock at the regional scale.

In the Vallcebre Basin the Garumnian overlies the marine nearshore deposits of the Terradets Formation, the Grey Garumnian begins with a succession of grey marl followed by alternating lignite and charophyte limestones (Fig. 1B). These rocks indicate the evolution from a brackish mud flat and lagoon to freshwater lacustrine and palustrine deposits (Villalba-Breva et al., 2012). The Lower Red Unit is the main subject of this study. In the Vallcebre Basin it displays up to 400 m of claystones and siltstones showing a strong development of paleosoils with variegated grey, ochre, purple and reddish colours. The Lower Red Unit has been attributed to sedimentation mainly in marginal lagoon and fluvial floodplain depositional settings (Rosell et al., 2001; Oms et al., 2007; López-Martínez et al., 2009; Riera et al., 2009). The top of the Lower Red Unit is marked by the so-called "Reptile Sandstone", a fluviatile unit that crops out below the lacustrine Vallcebre Limestone Formation (Masriera and Ullastre, 1982). The Vallcebre Limestone Formation, up to 60 m thick, characterise the lower Paleocene deposits of the composite section. It is composed by micritic limestones, massive in aspect, with abundant karstic surfaces and widespread diagenetic features. The Vallcebre limestones were deposited under lacustrine to palustrine conditions submitted permanently to edaphic processes (López-Martínez et al., 2006) and have been dated as Danian (Feist and Colombo, 1983; Rosell et al., 2001).

The occurrence of charophytes in the Vallcebre Basin was already reported by Depape and Bataller (1931) with the description of the porocharacean *Chara malladae* (now *Feistiella malladae* (Bataller 1945) Villalba-Breva and Martín-Closas 2013) in the Grey Unit of Fígols. Feist and Colombo (1983) and Médus et al. (1988) studied with more detail the charophytes of this basin and described a succession of charophyte floras, which is characterized by *Peckichara cancellata* Grambast 1971 in the Grey Unit, while the Lower Red unit contained *Peckichara sertulata* Grambast 1971 and the clavatoracean *Septorella brachycera* Grambast 1971 (now *Clavator brachycerus* (Grambast 1971) Martín-Closas 1996). The characean gyrogonite *Microchara cristata* Grambast 1971 was found throughout the section (Feist and Colombo, 1983). This study assigned the Grey Unit and the Lower Red Unit of the Vallcebre Basin to the Maastrichtian. The same authors characterized the first Paleocene beds at the base of the Vallcebre limestone by the occurrence of *Sphaerochara edda* Soulié-Märsche 1971, *Nitellopsis (Campaniella) helicteres* (Brongniart 1822) Grambast and Soulié-Märsche 1972 and *Dughiella bacillaris* Feist-Castel, 1975. In recent years, the studies on charophytes from the Vallcebre Basin were devoted mainly to the taxonomy and palaeoecology of fossil charophytes from the Grey Unit (Villalba-Breva and Martín-Closas, 2011, Villalba-Breva et al., 2012).

Recently Oms et al (2007) studied the magnetostratigraphy of Garumnian of the Vallcebre Basin providing a tool for the calibration of the charophyte succession and allowing comparison with a similar study carried out by Galbrun et al (1993) in the Àger Basin.

4. Systematic Palaeontology

Division Charophyta Migula, 1897
Class Charophyceae Smith, 1938
Order Charales Lindley, 1836
Family Characeae Agardh, 1824
Genus *Peckichara* Grambast, 1957

Peckichara cancellata Grambast, 1971.
Fig. 2, A–C.

Peckichara cancellata sp. nov. Grambast 1971, pp. 23–25, figs. 12 and 13; pl. XVIII. figs. 1–6; pl. XIX, figs. 1–9; pl. XX, fig. 1.

Material. 125 gyrogonites from samples MT-10, MT-11.1 and MT-11.2 (Mina Tumí section, Vallcebre Basin).

Description. Gyrogonites medium to large in size, 640–933 μm high (mean 846 μm) and 577–920 μm wide (mean 803 μm), with an isopolarity index (ISI) ranging 89–123 (mean 104), prolate spheroidal (sometimes subprolate). Spiral cells 94–171 μm wide (mean 136 µm), flat, 6 to 8, most frequently 7 convolutions in lateral view. The ornamentation consists of a mid-cellular crest with perpendicular to oblique rods placed on the sides of the crest forming a reticule. These crests are attenuated near the apex and become wider to the base. The spiral cells are separated by a fine intercellular crest. The apex is flat with a poorly-marked periapical depression and outstanding apical nodules. The base is rounded and shows a basal pore, 30–65 µm in diameter (mean 45 µm).

Remarks. *P. cancellata* differs from other species like *P. sertulata* Grambast 1971, *Peckichara caperata* Grambast and Gutiérrez 1977 and *Peckichara cristatella* Grambast and Gutiérrez 1977, by its reticulate ornamentation, and its smaller size. Furthermore, it differs from *Peckichara pectinata* Grambast 1971, because the latter has a larger mid-cellular crest and the rods do not close spaces as in a net, which results in a comb-like ornamentation.

Distribution. This species is very common in the Campanian of Rognac in the Provence, and in the Languedoc, France (Grambast, 1971). It was also found in the Marnes d’Auzas, Plantaurel and Hautes–Corbières in the North Pyrenean basins (Tambareau et al., 1997; Laurent et al., 2002). In Spain, *P. cancellata* was found in the Maastrichtian of Calderón (Cuenca), in the south-western Iberian chain (Grambast, 1975), and in the lowermost Maastrichtian of the South Pyrenean basins of Vallcebre and Àger (Feist and Colombo, 1983; Médus et al., 1988; Masriera and Ullastre 1988, 1990; Galbrun et al., 1993; Villalba-Breva et al., 2012; Villalba-Breva and Martín-Closas, 2011, 2013).

-- Fig. 2 near here --

Peckichara serrata Vicente and Martín-Closas, sp. nov.

Fig. 2, D–I.

Derivation of name. From the Latin *serrata/serratus* (adj.), meaning sawed, referred to the ornamentation of the mid-cellular crest.

Holotype. Specimen 80814 from the Museu de Geologia del Seminari Conciliar de Barcelona (Catalonia, Spain). Fig. 2, D.

Paratype. Specimens 80815–80819 from the Museu de Geologia del Seminari Conciliar de Barcelona. Fig. 2, E–I.

Type locality. Marls below the limestone bed at meter 37 from the Mina Tumí section (42° 12' 8.79"N, 1° 47' 20.08"E coordinates) Vallcebre Basin, samples MT-11.1 and MT-11.2 (Fig. 4).

Material. About 70 gyrogonites from sample MT-11 and 5 specimens from sample MT-12 (Mina Tumí section, Vallcebre Basin).

Diagnosis. Gyrogonites medium in size (about 600 µm high) with ovoid, sometimes subprolate shape. Ornamentation formed by a mid-cellular crest with small perpendicular to oblique rods placed on both sides of it forming a reticulum and tubercles in form of sharp teeth distributed regularly upon the crest, from the apex to the base, forming a sawed crest. This kind of fructification it is closely related to *P. cancellata* but differs from it by its ca 200 µm smaller size and by the occurrence of sharp tubercules in the mid-cellular crest.

Description. Gyrogonite medium in size, 545–717 µm high (mean 616 µm) and 497–618 µm wide (mean 539 µm), with an isopolarity index (ISI) ranging 101–126 (mean 115), ovoid, sometimes subprolate in shape. Spiral cells 82–99 µm wide (mean 91), slightly concave, with 5 to 7, most frequently 6, convolutions in lateral view. The ornamentation consists of a mid-cellular crest showing small perpendicular to oblique rods placed on both sides of the crest, touching it, and reaching the suture, which results in a reticulum. The mid-cellular crest is provided with thin tubercles distributed regularly in the crest, from the apex to the base. The morphology of the tubercles might change depending on the calcification of the samples, poorly calcified gyrogonites develop individualized elongate tubercles with a dull ending (Fig. 2F). By contrast, well calcified specimens are like teeth of a saw-edge (Fig. 2I). The apex is flat without or with a poorly-marked periapical narrowing. Apical tubercles may occur at the end of the spiral cells. The base is rounded and shows a pentagonal basal pore, 35−50 µm in diameter (mean 44 µm).

Remarks. This new species is characterized by the smaller size of gyrogonites in comparison to *P. cancellata*. Biometrical analyses of two assemblages containing both *P. cancellata* and *P. serrata*, evidence that their respective height/width regression lines are oblique to each other. On the other hand, there are no midterm specimens between both populations as regards the size, shape and ornamentation. Feist and Colombo (1983) reported a "*P. cancellata* forme naine" in the Paleocene of the Vallcebre Basin, and considered it as a relic morphotype of *P. cancellata*. Unfortunately they do not provide any description or illustration that would help us in evaluating the equivalence with the material described here.

Distribution. This species was found so far only in the lower Maastrichtian of the Vallcebre Basin.

Peckichara sertulata Grambast, 1971

Fig. 2, J–L.

Peckichara sertulata sp. nov. Grambast 1971, pp. 25–27, figs. 14 and 15; pl. XX figs. 2–5; pl. XXI, figs. 1–7.

Material. About 100 gyrogonites from samples MT-10, MT-11.1 and MT-11.2 (Mina Tumí, Vallcebre Basin).

Description. Gyrogonites medium in size, 597–937 µm high (mean 771 µm) and 547–860 µm wide (mean 695 µm), with an isopolarity index (ISI) ranging 90–135 (mean 111), with ovoid shape. Six to eight convolutions visible in lateral view separated by fine intercellular suture occasionally forming a small crest. Spiral cells concave, 122 µm wide and ornamented with a generally thin mid-cellular crest that sometimes is undulated and contains small nodules. The mid-cellular crest disappears in the periapical zone, but develops apical tubercules. The apex is flat and shows a poorly marked periapical depression. Contrary to the apex, the mid-cellular crest is continuous to the base that is rounded and contains a basal pore about 47–77 µm in diameter (mean 62 µm).

Remarks. This species differs from other *Peckichara* ornamented with mid-cellular crest, such as *P. cristatella* Grambast and Gutiérrez1977 and *P. caperata* Grambast and Gutiérrez 1977*,* by its larger size and because these species are more spherical in shape and display a thinner mid-cellular crest.

Distribution. *P. sertulata* occurs in the Campanian and Maastrichtian of the Provence and the Languedoc, France (Grambast, 1971; Feist and Freytet, 1983; Massieux et al., 1985; Lepicard et al., 1985). In Spain, *P. sertulata* has been reported in the Maastrichtian of Calderón and Torrecilla (Cuenca province), in the south-western Iberian chain (Grambast, 1975) and in the Campanian to upper Maastrichtian of the South Pyrenean basins of Tremp, Àger, Coll de Nargó and Vallcebre (Feist and

Colombo, 1983; Médus et al., 1988; Masriera and Ullastre, 1988, 1990; López-Martínez et al., 2001; Villalba-Breva and Martín-Closas, 2013).

Peckichara toscarensis Feist and Colombo, 1983

Fig. 2, M–O.

Peckichara toscarensis sp. nov. Feist and Colombo 1983, pp. 314–315; pl. 3.figs. 1–5.

Material. Only 3 gyrogonites from CB-3 (Cal Borni section, Vallcebre Basin).

Description. Gyrogonites large in size, 880–1160 µm high (mean 1027 µm) and 800–1040 µm wide (mean 933 µm), with an isopolarity index (ISI) ranging 108–112 (mean 110), ovoid to ellipsoidal in shape. Spiral cells 120–160 µm wide (mean 147 µm) concave with 6 to 8 convolutions visible in lateral view. They are ornamented with a wide mid-cellular crest, sometimes undulated and disappearing near the apical zone. Apex flat or slightly rounded with small nodules, without periapical modifications. Base flat, sometimes rounded, with a pentagonal basal pore, star shaped, about.120–200 µm in diameter (mean 173 µm).

Remarks. This species differs from *P. sertulata* by its larger size and its wider mid-cellular crest.

Distribution. This species is only known from the southern Pyrenees. It was first reported in the Paleocene of Vallcebre and Campo (Feist and Colombo, 1983; Mèdus et al., 1988). Later, it was described in the Early Paleocene of the Àger Basin, mainly in the Fontllonga section (Mèdus et al., 1988; Masriera and Ullastre, 1990; Galbrun et al., 1993 and Mayr et al., 1999).

Peckichara llobregatensis Feist and Colombo, 1983

Fig. 2, P–R.

Peckichara llobregatensis sp. nov. Feist and Colombo 1983, pp. 315–316; pl. 3.figs. 6–10.

Material. About 50 gyrogonites from samples CB-3 and 2 from CB-4 (Cal Borni section, Vallcebre Basin).

Description. Gyrogonites medium in size, 484–742 μm high (mean 627 μm) and 533–717 μm wide (mean 617 μm), with an isopolarity index (ISI) ranging 84–111 (mean 104), ellipsoidal, sometimes prolate spheroidal in shape. Spiral cells 78–114 μm wide (mean 99 μm), slightly convex or flat, 5 to 7 convolutions, most commonly 6, visible in lateral view. They are ornamented with large, well individualized and prominent tubercules with the same width than the spiral cells and spaced at regular intervals. The ornamentation disappears in the periapical area, but apical nodules occur. Apex rounded or obtuse, with a moderate narrowing of the spiral cells in the periapical zone. Base rounded, sometimes pointed with a pentagonal basal pore, showing a small funnel 51–68 μm in diameter (mean 61 μm).

Remarks. Among all the species of *Peckichara* that are ornamented with tubercules, *P. varians* Grambast 1957 is the most similar to *P. llobregatensis*. However, the latter shows a smaller size and displays a lower number of convolutions. Besides, *Peckichara varians* is often ovoid or ellipsoidal in shape, in contrast with the constantly subglobulose shape of *P. llobregatensis*. The apex of *P. varians* displays stronger periapical modifications than *P. llobregatensis*. Also, the well-individualized rounded apical nodules of *P. llobregatensis* contrast with the large and irregular apical nodules of *P. varians*.

Distribution. *P. llobregatensis* was previously reported from the Danian of the Àger Basin (Galbrun et al., 1993) and the Thanetian of the Vallcebre Basin (Feist and Colombo, 1983), where it has its type locality. We report it also from the Danian of Vallcebre. Recent, unpublished data show that *P. llobregatensis* occurs as well in the Grey Unit, lower Maastrichtian, at Alzina, Tremp Basin, and Mirador del Cretaci, Coll de Nargó Basin, undermining previous assumptions by Riveline et al. (1996) that this species appeared close after the K/Pg boundary.

Genus *Microchara* Grambast, 1959

Microchara cristata Grambast, 1971

Fig. 3, A–D.

Microchara cristata sp. nov. Grambast 1971, pp. 35–36, figs. 22 and 23; pl. XXVIII. figs. 1–8; pl. XXIX, fig. 110.

Material. About 32 gyrogonites from samples MT-10 to MT-13, CP-1, CP-4, CP-15 and CP-16 (Mina Tumí and Coll de Pradell section, Vallcebre Basin).

Description. Gyrogonites of medium size, 642–769 µm high (mean 715 µm) and 571–634 µm wide (mean 598 µm), with an isopolarity index (ISI) ranging 113–132 (mean 120), mainly ovoid or subprolate (sometimes prolate spheroidal and rarely ellipsoidal) in shape. Seven to nine, most frequently nine, convolutions visible in lateral view with cells about 68–95 µm (mean 87 µm) in width. Spiral cells concave, ornamented with a mid-cellular crest parallel to the suture. Apex rounded with shallow, comma-shaped nodules that are lacking in some specimens. Base pointed, sometimes elongated in a short column, ended with a basal pentagonal pore, 55–62 µm in diameter.

Distribution. *M. cristata* has a large distribution in the Upper Cretaceous of Eurasia. It was reported from the Campanian and Maastrichtian of several localities in France (Grambast, 1971; Feist and Freytet, 1983; Massieux et al., 1985; Lepicard et al., 1985) and in the Maastrichtian of Romania (Villalba-Breva and Martín-Closas, 2013). In the context of the South Pyrenean basin, *M. cristata* occurs in the Maastrichtian of the Tremp, Àger, Coll de Nargó and Vallcebre basins (Feist and Colombo, 1983; Masriera and Ullastre, 1988; Villalba-Breva et al., 2012; Villalba-Breva and Martín-Closas, 2013). Furthermore, we also report *M. cristata* from the Maastrichtian and the base of the Paleocene in the Vallcebre Basin. Finally, it also occurs in the Late Cretaceous of China, at Shalamulun (Inner Mongolia), in the Junggar Basin, Xinjiang (Karczewska and Ziembinska-Tworzydlo, 1981; Liu 1987; Liu and Wu 1987).

Microchara nana Vicente and Martín-Closas, sp. nov.

Fig. 3, E–J.

Derivation of name. From the Latin adjective *nanus/nana*, referred to its extremely small size.

Holotype. Specimen 80820 from the Museu de Geologia del Seminari Conciliar de Barcelona (Catalonia, Spain). Fig. 3, E.

Paratype. Specimens 80821–80826 from the Museu de Geologia del Seminari Conciliar de Barcelona. Fig. 3, F–J

Type locality. Ochre claystone and siltstones at meter 103 from the Coll de Pradell section (42° 12' 12.54"N, 1° 46' 13.81"E) Vallcebre Basin, sample CP-4 (Fig. 4).
Material. About 136 gyrogonites from samples MT-1 to MT-6 and 98 gyrogonites from MT-10 to MT-14 (Mina Tumí section), 614 gyrogonites from CP-1 to CP-7 and CP-12 to CP-16 (Coll de Pradell section) and a few samples from CB-4 (Cal Borni), all belonging to the Vallcebre Basin.
Diagnosis. Gyrogonites very small in size (about 272 µm high) mainly ovoid or subprolate in shape, with about 6-8 convolutions, generally, with irregularly developed mid-cellular crest.
Description. Gyrogonites very small in size, 243–323 µm (mean 272 µm) high and 202–257 µm (mean 227 µm) wide, with an isopolarity index (ISI) ranging 102–149 (mean 120), mainly ovoid or subprolate (rarely spheroidal or ellipsoidal) in shape. Six to eight, most frequently seven, convolutions visible in lateral view. Spiral cells about 28–45 µm (mean 37 µm) in diameter, concave, generally ornamented with a mid-cellular crest parallel to the suture. Apex rounded, provided with shallow nodules, although some specimens may lack them. The base is generally rounded, rarely pointed or with a short column, and ends in a basal pentagonal pore, 29 µm in diameter.

This extremely abundant species shows a high polymorphism in the shape, ranging from ovoid, to subprolate or even spheroidal. Independently from the shape polimorphism, the variation in the ornamentation enables us to recognize four morphotypes. Morphotype I present cell sutures with a height similar to the mid-cellular crest. Morphotype II exhibits a thin mid-cellular crest. Morphotype III shows a thin mid-cellular crest that disappears progressively in the lower half of the gyrogonite. Morphotype IV is devoid of ornamentation. Worth noting is that the two dominant morphotypes of *M. nana*, are I and II with a 44% and 35% of the population studied respectively leaving only the 12% of the samples represented by the morphotypes III and IV.

Remarks. *M. nana* is similar to *M. cristata* in the occurrence of a mid-cellular crest, however they differ mainly in their size, which is more than 400 μm smaller in *M. nana,* and by the higher polymorphism of *M. cristata*. Additionally the type population of *M. cristata* usually has a pointed base, sometimes with a short column, whilst the new species generally lacks this feature.

Distribution. This species is very abundant in most charophyte-bearing beds of Coll de Pradell and Mina Tumí, and poorly represented in Cal Borni, Vallcebre Basin. Its whole range is lower to upper Maastrichtian and lower Danian.

Microchara punctata Feist and Colombo, 1983

Fig. 3, K–N.

Microchara punctata sp. nov. Feist and Colombo 1983, pp. 311–312; pl. 1.figs. 13–18.

Material. Few specimens from samples MT-10, MT-12, MT-14, CP-2 and CP-5. About 250 gyrogonites from samples CP-9 to CP-11 (Coll de Pradell section, Vallcebre Basin).

Description. Gyrogonites very small, 243–378 μm high (mean 326 μm) and 231–337 μm wide (mean 282 μm), with an isopolarity index (ISI) ranging 86-137 (mean 116), ovoid (sometimes prolate spheroidal or subprolate) in shape. Six to eight most frequently seven convolutions visible in lateral view, 32–56 μm (mean 42 μm) wide. Spiral cells flat or slightly concave, ornamented with rounded tubercles spaced at regular intervals, parallel to the suture and attenuated in the apical zone. Sometimes these tubercles widen laterally to form a crest by fusion of adjacent tubercules. The apex is slightly rounded to round with apical tubercules similar to the lateral ornamentation. No narrowing is found in the periapical zone. Base generally pointed with a large pentagonal basal pore, sometimes showing a small basal funnel, 26 µm in diameter.

Remarks. *M. punctata* is smaller than *Microchara hystrix* Grambast 1959 and has a smaller number of convolutions. Both *Microchara pachythelys* Grambast 1977 and *M. hystrix* Grambast 1959 display a much more irregular distribution of the tubercules. Finally, *M. punctuata* Riveline 1986 is slightly larger than *M. punctata*, and does not display apical tubercules; instead, it is provided with an apical cap.

Distribution. *M. punctata* was first reported from the lower Maastrichtian of the Barranc de la Posa section, Isona, Tremp Basin by Feist and Colombo (1983). Ullastre and Masriera (2006) reported this species in the lower Maastrichtian (Grey Garumnian) at Sallent, Coll de Nargó Basin. Here, we document the occurrence of this species in the lower and upper Maastrichtian of the Vallcebre Basin.

Genus *Lychnothamnus* (Ruprecht, 1845) Leonhardi, 1863 emend. A. Braun in Braun and Nordstedt, 1882

Lychnothamnus aff. *curryi* (Grambast 1977) nov. comb. Vicente and Martín-Closas 2014

Fig. 3, O–R.

Stephanochara curryi n. sp. Grambast 1977, pp. 23–24, figs. 15; pl. V. figs. 4–6.

Material. 17 gyrogonites from sample CB-3 (Cal Borni section, Vallcebre Basin).

Description. Gyrogonites medium to large, 655–920 µm high (mean 762 µm) and 580–860 µm wide (mean 690 µm), with an isopolarity index (ISI) ranging 88–126 (mean 114), ellipsoidal to ovoid in shape. Spiral cells 88-125 µm wide (mean 103 µm), flat to slightly convex, with 6 to 8, most frequently 7 convolutions in lateral view. They are devoid of ornamentation but in some cases show bicarinate sutures. The apex is flat with a marked apical thinning. The spiral cells widen at the apical end and show well-individualized apical nodules. The base is elongated with a superficial and wide pore, rarely showing a star-shaped funnel, 60–115 µm across (mean 84 µm).

Remarks. This small population shows enough features to be assigned to genus *Lychnothamnus* following the criteria of Soulié-Märsche (1989), but the reduced number of gyrogonites available makes the specific attribution somewhat difficult. It differs from the type population of *L. curryi* in its thinner spiral cells and a higher number of convolutions.

Distribution. This species was reported first from the lower Eocene of Woolwich Beds at Swanscombe, England by Grambast (1977). Later, Riveline (1986) reported a *Stephanochara* cf. *curryi* from the lower Eocene of the Paris Basin. If the attribution of the material described will confirmed, this would be the oldest occurence of *L. curryi* in the Paleocene.

Family Clavatoraceae Pia, 1927

Genus *Clavator* Peck, 1941

Clavator brachycerus (Grambast, 1962) Martín-Closas, 1996

Fig. 3, S–U.

Septorella brachycera sp. nov. Grambast 1962, pp. 69–71, fig. 1.

Clavator brachycerus (Grambast 1962) Martín-Closas 1996 comb. nov., p. 280. figs. 10–11.

Heptorella brachycera Grambast 1962 – Feist and Grambast-Fessard in Feist et al., 2005, p. 110, fig. 56, 1a–c.

Material. 3644 utricles from MT-10, MT-11.1, MT-11.2 and MT-12 (Mina Tumí section, Vallcebre Basin)

Description. Utricles medium to large, 600–1160 µm high (mean 830 µm) and 440–1120 µm wide (mean 867 µm), showing an inverted pyramidal shape. The internal utricular layer is nodular. The external utricular layer is composed by 5 to 7, mainly 6 bract-cells, directly attached to a basal branchlet. Each bract-cell bears a fan of cells at its tip that correspond to what Grambast (1962) termed "a short horn" in the surface of the utricle. There are 12 elements in each fan: 3 apical filiforms cells, 2 lateral triangular cells and 7 long basal cells. The apex may be completely closed or is broken after germination, as already reported by Massieux et al. (1979).

Remarks. The presence or absence of an apical pore was the main feature to distinguish *C. brachycerus* (Grambast, 1971) Martín-Closas, 1996 and *Clavator ultimus* (Grambast, 1971) Martín-Closas, 1996 (=*Septorella ultima* Grambast 1971) according to Grambast (1962). The closure of the ancestral apical pore in *C. ultimus* was seen by Grambast (1974) as inability of the species to germinate and the reason for the extinction of this last clavatoracean in Europe. This viewpoint was challenged by Massieux et al. (1979) who found that both species showed closed apexes and that germination occurred by broking the apical part of the utricule. She proposed that the bract cell number and the size of the fructifications could allow distinction of both species, *C. ultimus* bearing a larger utricule than *C. brachycerus* with 8−9 instead of 5−7 lateral bract cells. The later viewpoint is followed here.

Distribution. *C. brachycerus* was only distributed in the Late Cretaceous of south-western Europe. In Spain it was reported from the Tremp, Àger, Coll de Nargó and Vallcebre basins (Feist and Colombo, 1983; Ullastre and Masriera, 1983; Masriera and Ullastre 1988, 1990; Villalba-Breva and Martín-Closas 2013). In France it was found in the Campanian of the Provence and Campanian-Maastrichtian of the Languedoc (Grambast, 1962; Massieux et al., 1979, 1985, 1987; Feist and Freytet, 1983).

--------------------------------------- Fig. 3 near here --

5. Sedimentology, taphonomy and palaeoecology

With the aim of understanding the relationship between the environment and the presence or absence of biostratigraphic useful species, sedimentological analysis coupled with taphonomical studies were carried out in the three sections sampled. Taphonomical features, such as abrasion of the fructification or the association of different organs of the same plant are useful to clarify the degree of autochthony or allochthony of the charophyte remains.

5.1. Lower Red Unit

Deposits of the Lower Red Unit show an alternation of variegated claystones and siltstones, occasionally interbedded with charophyte-limestone, oncolite-rich beds and sandstone. The succession displays a marked cyclicity which is easily recognized by the colour change in claystones and siltstones. From the sedimentological viewpoint, three main intervals have been distinguished (Fig. 4):

5.1.1. First interval

Description — This interval is build up by 160 m of claystones forming cycles, 2–7 m thick, with dark grey mottled claystones at the base followed by ochre claystones. Occasionally, these cycles alternate with fine to very fine-grained sandstone beds. A characteristic 0.5 m thick charophyte-limestone (sample CE in Fig. 4) occurs in the middle part of the interval and is useful to correlate different outcrops of the area. This wackstone-packstone is mainly formed by thalli of *Munieria grambastii* Bystrický 1976 and *Charaxis* sp. and contains also gyrogonites belonging probably to *Microchara* sp., *Peckichara* sp., and a few clavatoracean utricles attributed to *C. brachycerus.* Other components are fragments of wood, eggshells, ostracodes, gastropods and intraclasts. The marl underlying the limestone bed supplied the richest assemblage of charophyte fructifications (Table 1) and thalli, with *M. cristata*, *M. nana*, *P. cancellata*, *P serrata*, *P. sertulata*, *C. brachycerus*, along with fragments of wood, eroded fragments of gastropod shells and operculi, ostracodes, vertebrate eggshells and indeterminate bone fragments. Most charophyte remains are well preserved gyrogonites and utricles and were attributed to autochthonous assemblages. This interval was mainly studied in the Mina Tumí outcrop, where it is clearly overlying the coal-bearing beds of the Grey Unit.

Interpretation — The grayish claystones are attributed to deposits of the marginal, freshwater part of the lagoon, episodically with lacustrine facies, passing upward to ochre claystones of distal alluvial facies (Oms et al., 2007; Riera et al., 2009). Mottling represent the development of hydromorphic soils in the marginal lagoon, with alternating reducing and oxidizing conditions during seasonal fluctuation of the water table (see Kraus and Aslan, 1993). The absence of edaphic nodules and the presence of rootlet marks developed in a moist or wet substrate correspond to sub-humid environments (Mader, 1995; Cojan and Moreau, 2006). These features identify palustrine environments, with a watertable that changed in depth but was constant enough for submerged vegetation to thrive. The cyclicity represents a repeated shift from the permanently inundated, mainly freshwater lagoon, where most charophytes were growing, to the lagoonal margins with enhanced alluvial influence and a conspicuous development of helophytic vegetation. Microfacies analysis of the only lacustrine limestone available shows an abundant presence of *M. grambastii* over other charophyte remains suggesting a very shallow environment (Villalba-Breva et al., 2012). This is consistent with the abundance of intraclasts and fragmented mollusc shells which would indicate lakeshore areas (Freytet and Plaziat, 1982; Climent-Domènech et al., 2009).

--------------------------------------- Table 1 near here --

5.1.1. Second interval

Description — This interval is 191 m thick and mainly formed by a succession of 4–10 metric cycles of light grey to ochre claystones at the base passing upward to purple, highly bioturbated claystones. The latter deposit also contains abundant edaphic features such as mottling and lime nodules. A few oncolite-rich beds and a stromatolite horizon occur at the base of the first cycles of this interval. Some of these beds are oncolite-supported limestones with a fine-grained sandstone matrix, while small oncolites can also be interspersed in clays. Upward in the section, fine to very fine-grained channelized sandstones with large-scale cross-bedding become more abundant. Charophytes occur mainly in ochre and light grey claystones and the assemblage is limited to *M. nana* and *M. punctata* (Table 1) with well preserved gyrogonites. These gyrogonites along with associated articulated ostracode shells, most of them attributed to genus *Frambocythere* Colin 1980, suggest autochthony. In contrast, there are abundant fragments of operculi and shells of gastropods, probably transported. Vertebrate remains are represented by a few fragments of dinosaur and lizard eggshells, and rarely crocodrilomorph and fish teeth. Most remarkable is the occurrence of planktonic foraminifera, with 32 species identified, in ochre and light grey claystones, associated to the oncolite beds of this interval (Table 2). Their preservation is usually poor to moderate (Fig. 5).

Interpretation — This interval shows increased evidence of sub-aerial exposure in the floodplain, with an upward increase of the fluvial influence. The grey claystone beds at the base of cycles represent temporary ponds with sufficient water depth for the growth of species-poor charophyte meadows dominated by *M. punctata*. Purple claystones of the upper part of cycles are rich in hematite (Fe_2O_3) (Kraus and Hasiotis, 2006). This, along with abundant mottling and edaphic nodules indicate an increased development of hydromorphic paleosoils in a context of a fluctuating watertable (Kraus and Aslan, 1993). Fine grained sandstone channels with large-scale cross-bedding are attributed to the lateral accretion of bars in a high sinuosity channel. The tractive facies are sometimes overlain by thin grey claystone that would correspond to deposition in fluvial oxbow lakes. Oncolite-supported limestones would correspond to small fluvial channels, while clay with interspersed oncolites suggests calm lacustrine conditions. In this interval, the cyclicity represents the shift from a temporarily inundated floodplain grown by charophytes and helophytic plant-communities (hydromorphic soils) to more sub-arid environments with abundant mottling colour and edaphic nodules (Mader, 1995; Cojan and Moreau, 2006).

--------------------------------------- Table 2 near here ---------------------------------------

5.1.1. Third interval

Description — The third interval was studied in the upper part of the Coll de Pradell outcrop. It is up to 76 m thick, displays 4–10 m thick cycles formed by ochre claystones at the base passing upward to red claystones that are often intercalated with fine-grained, channelized sandstone. The top of the third interval forms a conspicuous coarse-sandstone and microconglomerate unit, called locally the "Reptile Sandstone" (Masriera and Ullastre, 1982) that was studied in the Cal Borni section. Charophytes become rare in the third interval and are limited to well preserved gyrogonites of *M. nana* (Table 1) occurring in the ochre claystones. As in the second interval, here again some beds contain planktonic foraminifera (Table 2).

--------------------------------------- Fig. 4 near here --

Interpretation — The ochre beds at the base of cycles from the upper interval are the result of a relatively higher water table in the floodplain with poorly developed hydromorphic soils. The increasing size of the channels in this interval reflects the expansion of the fluvial system. The sedimentary features of the "Reptile Sandstone" suggest deposition in a braided-river system with a relative high energy (Rosell et al., 2001, Vila et al, 2013). The cycles in this interval show a progressive dominance of fluvial facies (channelized sandstone) over floodplain facies, which were generally exposed and only contained a few temporary ponds with species-poor charophyte meadows.

The three intervals represent a vertical sedimentary evolution that influenced the charophyte distribution, passing upward from species-rich assemblages (ca 5-6 species) of the first interval to species-poor charophyte assemblages (1-2 species) in the second interval, eventually disappearing in the third interval. The reduction in the number of species occurs in parallel with a facies change, from the freshwater part of a lagoon to largely exposed and terrigenic floodplains, where only temporary ponds with a high terrigenic input allowed for charophyte development. Probably these floodplain ponds were usually turbid, like those reported in a similar sedimentary context of the Eocene by Sanjuan and Martín-Closas (2012). This vertical evolution is coupled with a marked decrease of the mean size of the fructifications. Ochre palustrine claystones in the generally exposed floodplain deposits of the third interval contained only tiny gyrogonites (generally less than 300 µm across) of *M. nana* and *M. punctata*, suggesting some type of ecological restriction. However, *M. punctata* occurs along the section in a wide range of submerged facies (lacustrine limestone, grey or ochre floodplain claystones in hydromorphic soils), indicating that it grew in a wide number of different habitats, which make this species appropriate for biostratigraphic use.

---------------------------------- Fig. 5 near here---

5.2. Base of the Vallcebre Limestone Formation

Description — This formation is generally formed by massive limestone beds with nodulization, recristalization and karstification. In the Vallcebre Basin this unit reaches his maximum thickness, ca. 60 m. The base is characterised by an alternation of pale limestone and relatively dark (organic-rich) marls. The main thickness of the Vallcebre limestone is made up of a succession of small metric cycles, with lacustrine limestone at the base, and showing nodulization and karstification to the top.

The basal dark claystones contain the first remains of Paleocene charophytes with well-preserved gyrogonites of *P. toscarensis, P. llobregatensis*, *M. cristata*, *M. nana* and *L.* aff. *curryi*, with fragmented gastropod remains. Previous biostratigraphic studies on this formation describe a larger number of Paleocene charophytes upward in the section, mainly formed by *P. toscarensis*, *D. bacillaris*, *S. edda* and *N. helicteres* (Feist and Colombo, 1983; Médus et al., 1988).

Interpretation — This unit was formed under lacustrine conditions (Rosell et al., 2001; López-Martínez et al., 2006) in Vallcebre, although in the Àger Basin, Mayr et al. (1999) evidenced marine influences based on the $^{87}Sr/^{86}Sr$ index of the equivalent limestone (Figuerola Formation). The cycles observed in the formation are related to lake shallowing processes (López-Martínez et al., 2006).

6. Biostratigraphy

The first attempt to characterize biostratigraphycally the non-marine Upper Cretaceous on the basis of charophytes was carried out by Grambast (1971) in the Provence basin. He described a succession of three charophyte assemblage zones. The first (La Gardanne-Girard Zone) made of *Septorella campylopoda* (Grambast, 1964) and *P.*

pectinata (Grambast, 1971) was attributed to the local non-marine stage Begudian, now correlated with the Campanian (Westphal and Durand, 1990). The second assemblage (Lower Rognac Zone), formed by *S. brachycera* (Grambast 1962) and *P. cancellata* (Grambast, 1971) was proposed as characteristic for the lower Rognacian local stage (upper Campanian–lower Maastrichtian according to Westphal and Durand, 1990) and finally the Upper Rognac Zone with *S. ultima* (Grambast, 1971) and *P. sertulata* (Grambast, 1971) was proposed for the upper Rognacian (upper Maastrichtian according to Westphal and Durand, 1990). New taxonomic, biostratigraphic and magnetostratigraphic data obtained by Feist and Colombo (1983), Médus et al. (1988) and Galbrun et al. (1993) in the southern Pyrenean basins resulted in the proposal of an improved charophyte biozonation for the European Upper Cretaceous by Feist in Riveline et al. (1996), that remains unchanged since then.

In comparison with the Àger Basin and the Rognacian type section of the Provence, the succession in Vallcebre is almost completely devoid of lacustrine facies, which are only well-developed to the base. Most of the Lower Red Unit only includes charophyte species able to withstand a strong fluctuation of the water table and a high terrigenic input, in temporary ponds of a floodplain. This explains why species characteristic of lacustrine environments, such as *P. sertulata* or *C. brachycerus*, were not widespread.

The charophyte succession of the Maastrichtian of Vallcebre begins with the coal-bearing deposits of the Grey Unit that contain *P. cancellata* and *M. cristata* (Feist and Colombo, 1983; Villalba-Breva and Martín-Closas, 2011; Villalba-Breva et al. 2012). The first interval of the Lower Red Unit shows an assemblage dominated by *C. brachycerus* associated with *P. cancellata*, *P. serrata*, *P. sertulata*, *M. cristata*, *M. nana* and *M. punctata* (Fig. 4). Following upward in the succession, the second interval of the Lower Red Unit shows a reduced species richness with only two species. This assemblage, formed by *M. punctata* and *M. nana*, grew – as stated above – in temporary floodplain ponds submitted to a high terrigenous inputs and a fluctuating water table. The third interval contains only *M. nana* and is poorly characterized from the biostratigraphic viewpoint. Finally, the lacustrine deposits at the base of the Vallcebre Limestone Formation contain *P. llobregatensis*, *P. toscarensis*, *L.* aff. *curryi*, *M. cristata* and *M. nana*.

The biozonation of Riveline (1996) for the Maastrichtian is difficult to follow in the Vallcebre Basin. The P. cancellata Biozone is recognizable at the base of the section (Grey Unit and base of the Lower Red Unit) and is conserved in the new local biozonation we propose.

The charophyte succession at Vallcebre lacks *C. ultimus*, index species of the S. ultima Biozone of Riveline et al. (1996). This species was expected to occur in the lacustrine deposits of the lower interval of the Lower Red Unit, according to the magnetostratigraphic data available in Vallcebre and the range of this species provided by Galbrun et al (1993), but it is not represented, even in the lacustrine facies that this interval contains. Its absence may be related to palaeoecological constraints that are yet to be defined for this species. Additionally, the total biostratigraphic range of *C. ultimus* in the Pyrenean basins and elsewhere is poorly known, since this species only occurs in sparse localities. The second and third intervals of the Vallcebre section correspond in part with the range of M. cristata and Peckichara sp. 1 Biozones, which are poorly characterized, as already explained above (section 1). Taking into account this situation, the new Biozone P. punctata is proposed below to characterise part of the time interval covered by the Biozones S. ultima, M. cristata and P.sp.1 of Riveline et al. (1996).

The P. llobregatensis Biozone, which marks the beginning of the Paleocene, has been recognized at the top of the section (base of the Vallcebre Limestone Formation). However, we know from own unpublished data that the index species already occurs in the Maastrichtian of Tremp and Coll de Nargó Basins, undermining the utility of *P. llobregatensis* to characterize the lower Danian deposits. In consequence we propose to substitute it by the P. toscarenis Biozone created by Galbrun et al. (1993) for the same time interval.

In consequence with these observations a new local charophyte biozonation is proposed below. This biozonation intends to improve the limited use of the biozonation by Riveline et al. (1996) in Maastrichtian floodplain facies, coming over the reduced usefulness of *S. ultima* as a index species, the poor definition of biozones of M. cristata and Peckichara sp. 1 and the extended range of *P. llobregatensis*. The new biozones are calibrated to the GPTS with data from Oms et al. (2007) and compared with biostratigraphic data from planktonic foraminifera. In some samples, it has been found very scarce *ex situ* specimens of probably Santonian age such as *Hedbergella faldrini, H. delrioensis, H. simplex, Marginotruncana coronata* and *M. pseudolineianna*, whose last appearances are older than the Maastrichtian (Caron, 1985). Given the detrital nature and scarcity of specimens, it is difficult to determine whether the presence of the remaining species are the result of the erosion of older rocks (*ex situ* specimens appearing through reworking *sensu* Fernández-López [1991]) or reflects *in situ* specimens (*sensu* Fernández-López, 1991) that were landward transported by nekroplanktonic dispersal. We adopted a cautious scenario for the planktonic foraminifera associated with charophytes, assuming that all specimens were *ex situ* (reworked). Although reworked microfossils are often considered inappropriate for biostratigraphic studies, they can be used to estimate a minimum age for rocks containing them (Bralower et al., 1998; Pirkenseer et al., 2011).

Taking into account this limitation, the biochronological scale of foraminifera provided by Pérez-Rodríguez et al. (2012) was used here for an estimation of the minimum age in the Vallcebre section.

New charophyte local biozonation, and its calibration to the GPTS

Peckichara cancellata Biozone

Definition — Feist in Riveline et al. (1996) defined this biozone as a partial range zone between the first occurrence of *P. cancellata* and the first occurrence of *C. ultimus* (=*S. ultima*). In the Vallcebre Basin, the absence of this species leads us to redefine the upper boundary by the first occurrence of *M. punctata*. This boundary is ~ 2.6 Ma younger than the first appearance datum known for *C. ultimus*, as proposed by Riveline et al (1996).

Main correlation — This biozone was correlated by Feist in Riveline et al. (1996) with the early Maastrichtian palynofloras from Fígols-Vallcebre (Médus et al., 1988).

Species assemblage in the Vallcebre Basin — *P. cancellata*, *P. serrata*, *P. sertulata*, *M. cristata*, *M. nana* and *S. brachycera.*

Calibration to the GPTS — The base of this biozone has been reported in the Àger Basin within the reverse chron C32r (Galbrun et al., 1993), at ~ 73.26 Ma (boundary between chron C32r.2r and C32n.3n) according to Gradstein et al. (2004). However, Riveline et al. (1996) state that this biozone may start even within chron C33n. Calibration with the chron C32n was also provided in the Àger Basin (Galbrun et al., 1993). The top of this biozone is documented in the Mina Tumí section (Vallcebre Basin) within chron C31r providing an age of ~ 69.36 Ma.

Age — Early part of the Campanian to late part of the Maastrichtian.

Microchara punctata Biozone

Definition (new biozone) — Partial range zone comprising the interval between the first appearance of *M. punctata* and the first occurrence of *Peckichara* sp. 1. Comments — In comparison to the biozonation of Riveline et al. (1996) the biozone of M. punctata includes the interval covered by the upper part of the biozone of S. ultima, the whole range of M. cristata and the lower part of Peckichara sp. 1. The new biozone is intended to be useful for biostratigraphic characterisation of lacustrine and clastic floodplain facies on the basis of a species with a well-known range and palaeoecology.

Main correlation — The planktonic foraminiferal occurrences of *Contusotruncana plicata* and *Globotruncanita fareedi* (Fig. 5.N-P) associated to M. punctata in the Vallcebre section (Fig. 5.A-C), supports that the intervals 2 and 3 of this section belong at least to the late Maastrichtian, according to magneto and biostratigraphic calibration performed in the Zumaia section (Pérez-Rodríguez et al., 2012). Other Maastrichtian species represented, such as *Abathomphalus intermedius* and *Guembelitria blowi* (Table 2), and the absence of Danian species, support a Maastrichtian age for the intervals 2 and 3.

Species assemblage in the Vallcebre Basin — *M. punctata, M. cristata*, *M. nana*, *P. cancellata*, *P. sertulata*, *P. serrata* and *S. brachyvera*.

Calibration to the GPTS — The first occurrence of the index species has been recorded within the small normal interval in the middle part of the chron C31r, with an age of ~ 69.36 Ma at Mina Tumí and Coll de Pradell sections (Vallcebre Basin).

Age — Late part of the Maastrichtian.

Undefined interval

In the studied section only one species is represented in this interval, i. e. *M. nana*. This undefined interval is broadly equivalent to the Peckichara sp. 1 Biozone of the European biozonation by Riveline et al. (1996), and can be calibrated between chron C30n indicating an age of ~ 66.72 Ma (upper Maastrichtian) and chron C29r ~ 65.33 Ma (lower Paleocene).

Peckichara toscarensis Biozone

Definition — Total range zone defined between the first and last occurrences of *P. toscarensis*.

Main correlation — This biozone was correlated with the upper part of the nanoplankton biozone NP1 by Riveline et al. (1996).

Species assemblage in Vallcebre Basin — *D. bacillaris, N. helicteres, S. edda, P. toscarensis*, *P. llobregatensis, L.* aff. *curryi*, *M. cristata* and *M. nana*.

Calibration to the GPTS — The first occurrence of this species has been recorded within the upper part of the chron C29r at the Cal Borni outcrop, providing and age of ~ 65.33 Ma.

Age — Early Danian.

Comments — This biozone is equivalent to the P. toscarensis Biozone defined by Feist in Galbrun et al. (1993). The P. toscarensis Biozone, as defined here corresponds largely to the biozone of P. llobregatensis defined by Riveline et al. (1996). This biozone cannot be longer used to characterize the base of the Paleocene since the index species was recently found to occur in the Maastrichtian deposits of Tremp and Coll de Nargó basins.

7. Discussion and conclusions

Biostratigraphy of the European Upper Cretaceous charophytes began with the pioneering study of Grambast (1971) in the Provence (France). He first defined a succession of three charophyte zones similar to assemblage biozones (Oppel zones) based on species of genera *Peckichara* and *Clavator* (equivalent to *Septorella* according to Grambast's taxonomy). The same procedure was used later by M. Feist in Galbrun et al. (1993), when the first calibration to the GPTS of a charophyte-rich succession (the Fontllonga section in the Àger Basin) was carried out with magnetostratigraphic data. Galbrun et al. (1993) proposed a single superzone (M. cristata) subdivided in four assemblage zones by the association of this species with a number of other charophytes. Unfortunately these biozones were named in a complicate way (lower M. cristata, middle M. cristata, lower upper M. cristata, upper upper M. cristata) and the proposal had no continuation. In fact, three years later, the same author proposed a new biozonation (M. Feist in Riveline et al., 1996) based in the same data from Fontllonga built up with range zones. Partial range zones such as P. cancellata, and total range zones, such as S. ultima, intercalate with what the authors called "interval zones", meaning biostratigraphically undefined intervals characterised by the first and last appearances of index species from adjacent zones. To this type belongs the M. cristata

Zone. Additionally a biozone based on a poorly defined taxonomic index species, Peckichara sp.1, was added. In spite of these pitfalls there were no alternative proposals to this biozonation in the last two decades.

The application of the Upper Cretaceous charophyte biozonation by Riveline et al (1996) to other basins is not only difficult because of the poor definition of some biozones, but also because few is know about the facies and paleoecological control of the index species building the biozonation. *P. cancellata* and *M. cristata* were documented recently to occur in different vegetation belts in permanent freshwater lakes by Villalba-Breva an Martín-Closas (2011, 2013), while the same authors proposed a very shallow habitat in lakeshores for *C. brachycerus* (= *S. brachycera*). Nothing is known to date about the habitat of *C. ultimus* (= *S. ultima*) and in this study we document Maastrichtian characeans thriving in temporary lakes, such as *M. nana, M. cristata* and *M. punctata*. However the two latter species display a broader paleoecological spectrum, occurring as well in permanent lacustrine facies. Knowledge upon the palaeoecological constraints of charophytes is necessary to construct a biozonation.

Last but not least, a biozonation needs to be faithfully calibrated to the time scale. This is usually achieved in the case of non-marine biozonations either through direct correlation with magnetostratigraphic data or by indirect correlation to the time scale with biostratigraphic data from the marine realm, which are usually better calibrated. With these tools in hand we provide here an alternative biozonation for the non-marine Upper Cretaceous of the Vallcebre section, which can be compared with the proposal of

Galbrun et al. (1993) in the Àger basin and that may be completed with other future proposals in order to establish a truly synthetic European biozonation (Fig. 6).

-- Fig. 6 near here --

The P. cancellata Biozone created by Riveline et al. (1996) has been recognized and is retained in the new local biozonation proposed. However this biozone is enlarged to the top. In total, the new range of the P. cancellata Biozone extends from the base of chron C32r to chron C31r. The biozone of S. ultima by Riveline et al. (1996) has not been retained. The index species was not found in the Vallcebre Basin. The occurrence of this species is extremely discontinuous, even in the Provence, where the species was erected (Grambast, 1971), and in the Fontllonga section, where its range was defined based in only two occurrences (Galbrun et al., 1993). Before the use of *C. ultimus* is implemented in biostratigraphy, the palaeoecology of this species is to be clarified. In the newly proposed biozonation, the next biozone above P. cancellata is M. punctata. The index species allows characterization of chrons C31r to C30n and has a relatively broad palaeoecological spectrum in permanent lakes and temporary ponds, making it useful in biostratigraphy. The upper part of the Maastrichtian (chrons C30n to C29r) remains unsolved as to present knowledge in the Vallcebre Basin, since this interval corresponds to fluviatile facies with only two species represented with a large biostratigraphic range (*M. nana* and *M. cristata*). The base of the Paleocene can no longer be characterised by *P. llobregatensis*, as it could be with the biozonation of Riveline et al. (1996) on hand, since this species has been fond recently in the Maastrichtian from Tremp and Coll de Nargó, to the west of Vallcebre. In contrast, the base of the Danian appears to be well defined with the first appearance datum of *P.*

toscarensis. This species is easy to recognize and has been documented in a number of Pyrenean localities.

Future work is needed to characterize satisfactorily the charophyte biostratigraphy of the European Maastrichtian. The south Pyrenean basins appear to hold part of the clue to clarify this part of the charophyte biozonation but only two synclines, Àger and Vallcebre have been studied into detail to date, while the Tremp-Graus syncline and the Coll de Nargó syncline still need to be investigated for charophyte biostratigraphy beyond the pioneering work of Feist and Colombo (1993) and a few supplementary data obtained later (López-Martínez et al., 2001; Villalba-Breva and Martín-Closas, 2013).

Acknowledgements

This study is a contribution to projects CGL2011-27869, CGL2011-22912 and CGL2011-30069-C02-02 of the Spanish Min- istry of Economy and Competitiveness (MINECO), the second of them co-financed by the European Regional Development Fund This study was also funded by the Aragonian Departamento de Educacio□n y Ciencia (project DGA-E05). The research is part of the PhD dissertation of Alba Vicente, supported by a pre-doctoral grant of the Spanish Ministry of Economy and Competitiveness. We acknowledge the support of the project 2014 SGR 251 financed by the Autonomous Government of Catalonia. Dr. I. Soulie□ M€arsche and Dr. M. Feist (Univ. of Montpellier-II) are also acknowledged for providing the facilities necessary to compare the material from the Vallcebre syncline with the collections housed in the Institut des Sciences de l’E□volution (Univ. of Montpellier). Dr. Michael Schudack (Freie Universita€t Berlin), Dr. Ingeborg Soulie□ Ma€rsche (Univ. of Montpellier-II) and Dr. E. Koutsoukos greatly improved the manu- script during the peer review process. The English text was cor- rected by Christopher Evans (Universitat de Barcelona).

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Figure captions

Fig. 1. A. Geological map of the Pyrenees with location of the main synclines. B. Geological map of the studied area showing the location of the different sections, Coll de Pradell, Mina Tumí and Cal Borni. (Modified from Institut Cartogràfic de Catalunya, 2006).

Fig. 2. Charophyte fructifications from the Upper Cretaceous of Lower Red Unit (Tremp Fm.) from Vallcebre Syncline. A–C, *Peckichara cancellata*, A. lateral view, B. apical view and C. basal view. Sample MT-11. D–I, *Peckichara serrata* sp. nov., D lateral view (holotype, 80814), G. lateral view, E. apical view, H. basal view, F. poor calcified tubercles and I. calcified tubercles (paratypes 80815–80819). Sample MT-11. J–L. *Peckichara sertulata*, J. lateral view, K. apical view and L. basal view. Sample MT-11. M–O. *Peckichara toscarensis*, M. lateral view, N. apical view and O. basal view. Sample CB-3. P–R. *Peckichara llobregatensis*, P. lateral view, Q. apical view and R. basal view. Sample CB-3.

Fig. 3. Charophyte fructifications from the Upper Cretaceous of Lower Red Unit (Tremp Fm.) from Vallcebre Syncline. A–D, *Microchara cristata,* A-B. lateral view, C. apical view and D. basal view. Sample CB-3. E–J, *Microchara nana* sp. nov., E. lateral view of morphotypes I (holotype 80820), F. lateral view of morphotypes II, G. lateral view of morphotypes III, H. lateral view of morphotypes IV, I. apical view and J. basal view (paratypes 80821–80825). Sample CP-4. K–N, *Microchara punctata*, K-L. lateral view, M. apical view and N. basal view. Sample CP-10. O–R, *Lychnothamnus* aff. *curryi*, O-P. lateral view, Q. apical view and R. basal view. Sample CB-3. S-U,

Septorella brachycera, S. lateral view, T. apical view and U. basal view. Sample MT-11.

Fig. 4. Stratigraphic log of the Vallcebre composite sections showing position of charophyte samples, distribution of charophyte. Calibration with the magnetostratigraphy of Oms et al. (2007) and new biozonation proposed.

Fig. 5. Selected planktonic foraminiferal species of the Coll de Pradell section. A–C, *Contusotruncana plicata*, A. spiral view, B. lateral view and C. umbilical view. Sample CP-1; D–E, *Heterohelix planata*, D. frontal view and E. lateral view. Sample CP-3; F–G, *Globigerinelloides bollii*, F. frontal view and G. lateral view. Sample CP-16; H–J, *Globotruncana arca*, H. spiral view, I. lateral view and J. umbilical view. Sample CP-4; K–M, *Globotruncana aegyptiaca*, K. spiral view, L. lateral view and M. umbilical view. Sample CP-1; N–P, *Globotruncanita fareedi*, N. spiral view, O. lateral view and P. umbilical view. Sample CP-16; Q–S, *Hedbergella monmouthensis*, Q. umbilical view, R. lateral view and S. spiral view. Sample CP-15.

Fig. 6. Calibration of the Late Cretaceous-Early Paleocene new charophyte biozonation proposed with the GPTS (Grandstein et al., 2004). Review of the classical biozonations proposed by Galbrun et al. (1993) and Riveline et al. (1996).

Table 1. Abundance of charophyte species of the studied composite section on the Vallcebre Syncline.

Table 2: Distribution of planktonic foraminifera in the Coll de Pradell section. Relative abundances in the samples are indicated according to the following scale: A (abundant); C (common); and R (rare).