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The non-marine Lower Cretaceous of El Montsec thrust sheet (South-Central Pyrenees)

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ABSTRACT

The aim of this study is resolving uncertainties on the lithostratigraphy and chronostratigraphy of the non-marine Lower Cretaceous of El Montsec thrust sheet, which contains the most developed record of such facies in the central Pyrenees (Catalonia, Spain). The materials, traditionally known as "El Montsec Charophyte Limestones", overlie upper Berriasian marine limestones and belong in fact to two different stratigraphic units, separated by an angular unconformity, which is represented by an irregular karstic surface. The lower unit, newly defined as the Cova dels Lladres Intraclastic Limestone Formation, is composed by metric-scale fining-upward parasequences with black intraclast conglomerates at the base covered by charophyte limestones at the top. This first non-marine unit is attributed to the lower Barremian Eurasian charophyte biozone Atopochara trivolvis triquetra. The upper non-marine unit, (revisited El Montsec Charophyte Limestone), is made of metric-scale fining-upward parasequences of charophyte limestones. Ferruginous marls at the base of the upper unit have yielded charophytes of the Hemiclavator neimongolensis neimongolensis Eurasian charophyte biozone, corresponding to the early–late Barremian boundary. El Montsec Charophyte Limestone Formation transitions laterally to La Pedrera de Rúbies Lithographic Limestones Formation, which includes the two famous fossil Konservat Lagerstätten of La Pedrera de Meià and La Cabroa. In sum, the non-marine Lower Cretaceous succession of El Montsec thrust sheet shows at its base a stratigraphic gap ranging from the upper Berriasian to the early Barremian. Furthermore, the angular unconformity separating the Cova dels Lladres Formation and El Montsec Formation clearly reflects the strong tectonic activity associated with the Barremian Iberian rift, which has been linked with the opening of the Bay of Biscay.

KEYWORDS **Early Cretaceous. Iberia. Mesozoic rift. Lacustrine. Charales.**

INTRODUCTION

El Montsec thrust sheet is the geological unit containing most of the non-marine stratigraphic units and fossil record of the Pyrenean Lower Cretaceous. This record has been studied since the 19th Century, because of the exceptionally well-preserved plant and animal remains contained in the lithographic limestones of the Fossil Konservat Lagerstätten called La Pedrera de Rúbies (or La Pedrera de Meià) and La Cabroa (*e.g.* Martínez-Delclòs, 1991). In his pioneering study about the stratigraphy and basin evolution of the Pyrenean Jurassic and Lower Cretaceous, Peybernès (1976) included the whole non-marine stratigraphic record of that area in two laterally equivalent units, El Montsec Charophyte Limestone Formation (for "Calcaires à Charophytes du Montsech") and La Pedrera de Rúbies Lithographic Limestone Formation (for "Calcaires lithographiques à plantes et vertebrés de la Pedrera de Rubiés". He attributed them to the upper Berriasian–Valanginian, based on a biostratigraphic study of a poorly preserved ostracod fauna by Brenner *et al.* (1974). Later, Martín-Closas (1989), Ansorge (1991) and Martín-Closas and López-Morón (1995, 1996) showed that at La Cabroa paleontological site and in the Terradets gorge, El Montsec Charophyte Limestone Formation contained a characteristic charophyte flora from the lower Barremian. The latter authors pointed out that there were possibly two non-marine units of different age in what Peybernès (1976) called "Calcaires à Charophytes du Montsech". The upper one was of Barremian age, based on a characteristic charophyte assemblage, while an underlying non-marine formation, provisionally was assigned to the upper Berriasian–lower Valanginian age. The same authors continued to assign the lithographic limestones to this lower unit. This interpretation was used to establish the lithostratigraphic framework of the Lower Cretaceous of El Montsec thrust sheet in several geological maps including the 1:25.000 map of Pi *et al.* (2003). Thereafter, a more detailed study of the Terradets gorge section, showed that the lithographic limestones belonged to the Barremian part of the non-marine succession (Gomez *et al.*, 2015: suppl. materials). As a consequence, some confusion has arisen about the lithostratigraphy of the "Calcaires à Charophytes du Montsech" of Peybernès (1976). Some authors considered them as belonging entirely to the late Berriasian–early Valanginian (*e.g.* Berástegui *et al.*, 2002; Robador and García-Senz, 2004), while others placed them completely in the early Barremian (*e.g.* García-Senz and Muñoz, 2019; Gil-Delgado *et al.*, 2023a). The present study aims to clarify uncertainties on the stratigraphic record, sedimentological features and age of the non-marine Lower Cretaceous of El Montsec thrust sheet in the best exposed and most complete section in the Terradets gorge.

GEOLOGICAL SETTING

El Montsec thrust sheet is located in the South-Central Pyrenees and corresponds to one of the external-most thrusts of the Pyrenees (Fig. 1). It is bounded to the south by El Montsec frontal thrust over the Serres Marginals thrust sheet and to the north by the frontal thrust of the Bóixols thrust sheet (Séguret, 1972). El Montsec thrust sheet bears a wide syncline that contains up to 3000m of sedimentary record comprising: i) the uppermost Triassic to Lower Cretaceous deposits dominated by dolostones and limestones accumulated within a Mesozoic rift at the northern margin of the Iberian plate, ii) a very thick succession of mainly Upper Cretaceous carbonates and siliciclastic materials corresponding to the Mesozoic post-rift stage and the early syn-orogenic deposits of the Pyrenees, and finally, iii) the largely terrigenous Palaeogene infill of the Tremp-Graus basin, deposited piggy-back on El Montsec thrust sheet during and after its emplacement. The present study concerns the Lower Cretaceous record corresponding to the Mesozoic Iberian rift.

The uppermost Triassic to Lower Cretaceous succession of El Montsec thrust sheet was deposited within a half-graben, referred to as El Montsec Basin by García-Senz and Muñoz (2019), which is largely oriented northeast to southwest between the present-day Bóixols and El Montsec thrusts. According to the same authors, both thrusts represent the Mesozoic normal faults bounding the basin, inverted during the Paleogene compression. García-Senz and Muñoz (2019) also considered El Montsec Basin as being part of the hanging wall and rift shoulder of the more subsident Organyà Basin (Bóixols thrust sheet).

The Upper Triassic of El Montsec Basin is mainly represented by Keuper evaporites, which now crop out near the frontal thrusts since they were involved in the thrust detachment during the Pyrenean compression (Pi *et al.*, 2003). The Jurassic deposits of El Montsec thrust sheet are largely dolomitic. According to Peybernès (1976), Souquet (1988), Aurell and Meléndez (2002) and Meléndez and Aurell (2004) the Jurassic of El Montsec can be characterized as follows: i) Lias. The Lower Jurassic begins with dominant dolostones that are richer in evaporites to the base and shift to oolitic limestones to the top. The middle and upper Lias are richer in marls. ii) Dogger. The Middle Jurassic is represented by three sedimentary sequences, in total up to 20m thick. The first is represented by limestones rich in *Gryphaea*, while the second contains oncolitic limestones with bryozoans, serpulids and echinoderms. The upper sequence is formed by white massive bioclastic limestones that are rich in foraminifera. The so-called "Lower Dolomite" lies above this, measuring up to 350m thickness, and comprises the

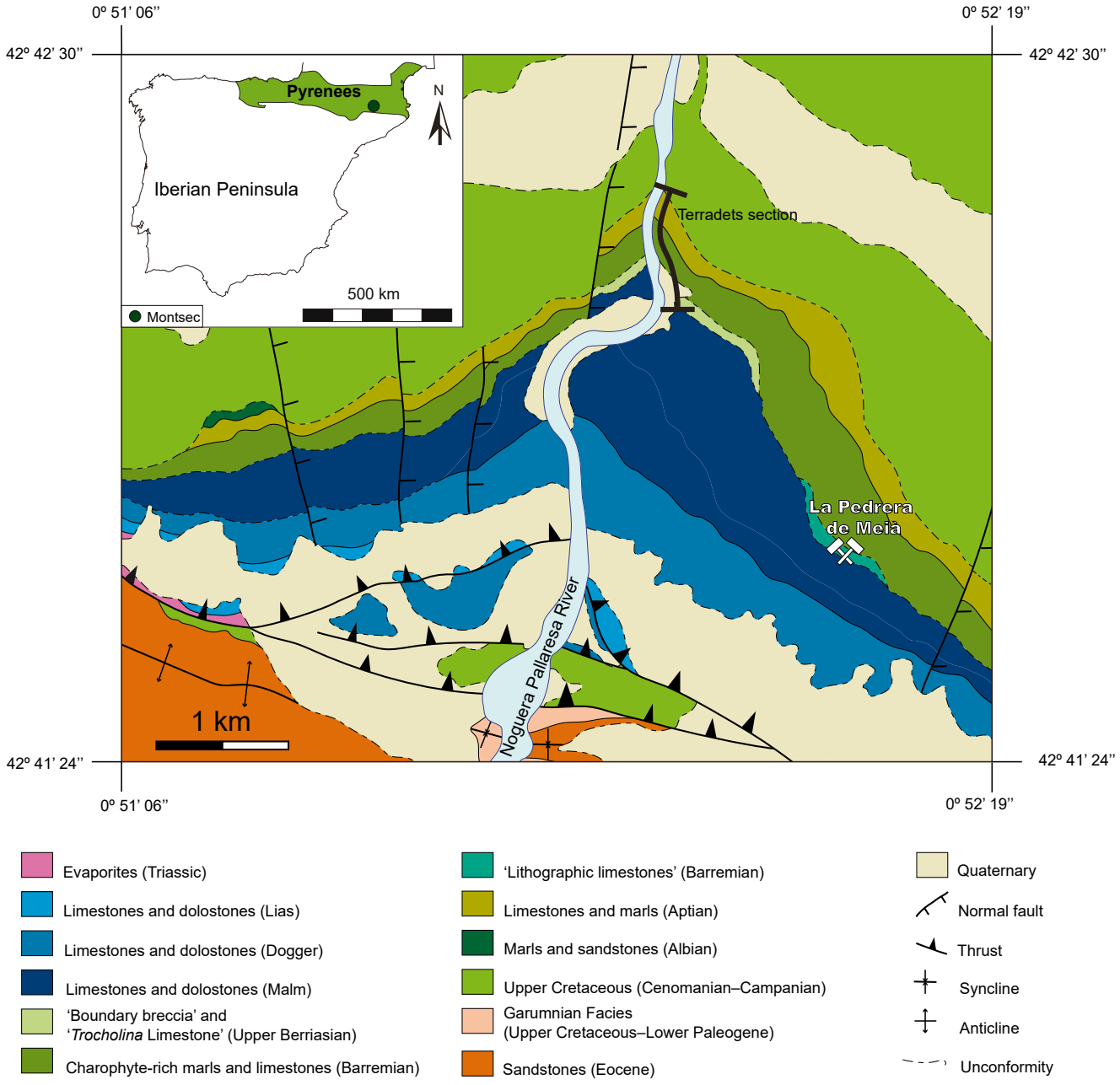

FIGURE 1. Geological map of the study area in the El Montsec thrust sheet, showing the location of the Terradets gorge section. Modified from Pi *et al.* (2003).

Dogger-Malm boundary. iii) Malm. The Upper Jurassic is again largely dolomitized in El Montsec thrust sheet. Above the "Lower Dolomite", extending from the Oxfordian into the Kimmeridgian, lies a succession of limestones and dolostones. The limestone intercalations, about 150m thick, show to the base limestones rich in dasycladaleans, followed by finely laminated limestones, limestones rich in the foraminifer *Everticyclamina virguliana* and, finally, limestones with *Anchispirocyclina lusitanica* and coprolites.

The Lower Cretaceous of El Montsec Basin was first characterized by Peybernès (1976), who defined several informal lithostratigraphic units. Thereafter, some of these units, precisely those to which Peybernès (1976) assigned a type locality, were considered formal lithostratigraphic units, *i.e.* formations. Modern syntheses by Berástegui *et al.* (2002), Robador and García-Senz (2004) and García-Senz and Muñoz (2019), will be reviewed in more detail in the next section (Fig. 2). The Lower Cretaceous record begins with a massive breccia, called the Boundary Breccia ("Brèche

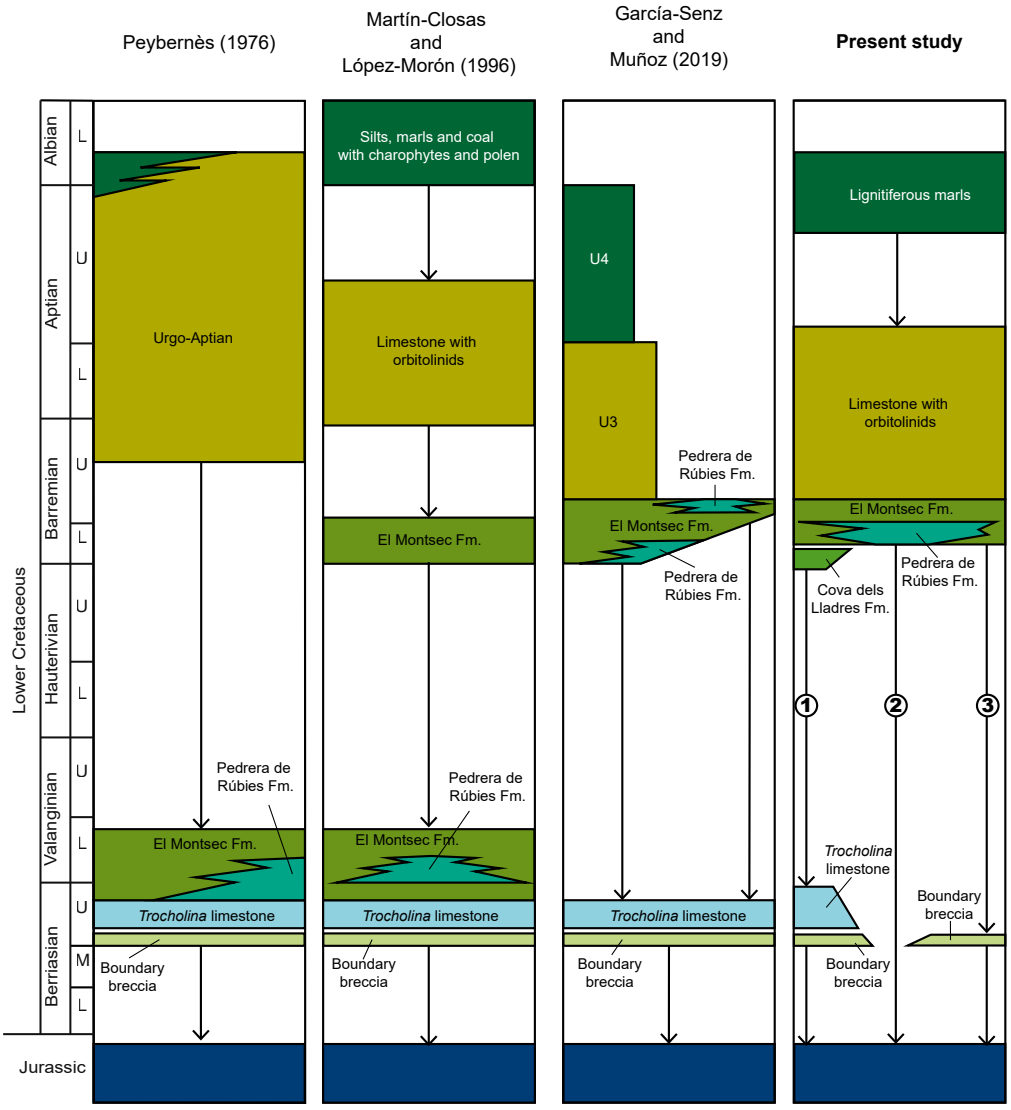

FIGURE 2. Lithostratigraphic framework of the Lower Cretaceous of El Montsec. Legend: 1. Terradets gorge section, 2. La Pedrera outcrop, 3. La Cabroa outcrop.

limite" by Peybernès, 1976), 27m thick, deposited in angular unconformity upon the Upper Jurassic dolostones, and overlain by limestones rich in benthic foraminifera called *Trocholina* and dasycladaleans Limestone (for "Calcaires à Trocholines et dasycladacées") by Peybernès (1976), about 11.5m thick. These units have been assigned to the upper Berriasian. A non-marine succession (up to 120m thick) follows, which Peybernès (1976) named "Calcaires à Charophytes du Montsech", which are the subject of the present study. This unit was first attributed by Peybernès (1976) to the upper Berriasian to lower Valanginian but later was considered in part belonging to the Barremian (*e.g.* Martín-Closas and López-Morón, 1996). This non-marine limestone is overlain by Urgonian limestone (for the "Calcaires urgo-aptiens inférieurs" of Peybernès, 1976), up to 40m thick, assigned to the late Barremian to early Aptian (Peybernès, 1976; Schroeder *et al.*, 1982). The uppermost deposits of the Lower Cretaceous correspond to the Lignitic marl and marlstone with *Pseudochofattella* (for "Marnes et marno-calcaires ligniteux à Pseudochoffattelles") of Peybernès (1976), which are several meters thick and have been assigned to the late Aptian. This unit underlies the regionally widespread Cenomanian *Praealveolina* limestone.

The Lower Cretaceous succession of El Montsec thrust sheet differs substantially from the succession observed in the neighbouring Organyà Basin (Bóixols thrust sheet) to the north. Above the Boundary Breccia and the "*Trocholina* and dasycladaleans Limestone" a several hundred meter thick shallow marine Barremian succession, called the Prada Formation, crops out in Organyà, with very

few, thin non-marine intercalations. The Prada Formation is overlain by basinal lower Aptian and Albian marls rich in ammonites (*e.g.* Cabó Marls Formation, Senyús Marls Formation). Locally, small carbonate platforms rich in corals and rudists occur, showing eastwards progradation against these deeper marine marls (Berástegui *et al.*, 1995; García-Senz and Muñoz, 2019).

MATERIAL AND METHODS

The Lower Cretaceous non-marine deposits of El Montsec thrust sheet have been studied in detail, both from the stratigraphic and the paleontological viewpoints, along the Terradets gorge section, where these deposits reach their maximum thickness and stratigraphic completion. The 180m thick section was studied following the C-13 road, south of the Font de les Bagasses parking area, with the base located at the coordinates 42º01'42.35"N and 00º52'59.93"E and the top at 42º01'52.21"N and 00º52'59,29"E. The section was logged at 1:100 and about 40 rock samples were collected to characterize the facies and microfacies as well as the age of the succession. The rock samples were sliced and thin sections about 30μm thick were prepared and studied under a microscope. Samples of marls were disaggregated in a solution of water, hydrogen peroxide and calcium carbonate before being wet washed with meshes of 1mm, 500μm and 200μm mesh size. The residues were screened under the binocular microscope to pick up the microfossils, especially charophyte gyrogonites and utricles. Thin sections were studied under a Motic BA 310 microscope and photographed by using Motic Images Plus 2.0 software. Charophyte fructifications were studied and photographed with a Quanta 250 Scanning Electron Microscope at the Centres Científics i Tecnològics of the University of Barcelona (CCiTUB). Thin sections and micropaleontological slides are being kept at the Department of Earth and Ocean Dynamics, University of Barcelona.

RESULTS

The non-marine Lower Cretaceous succession of El Montsec thrust sheet is revisited in the stratigraphic section of the Terradets gorge, which represents the most complete record of the Lower Cretaceous in the area. For descriptive purposes the succession was studied here in detail beginning at the base of the Lower Cretaceous to the top of the non-marine units (Fig. 3).

Boundary Breccia

This informal unit, first defined by Peybernès (1976), crops out extensively in the Lower Cretaceous of the Pyrenees. In the Organyà Basin (Bóixols thrust sheet), for instance, it has been formally defined as the Pont de la Torre Formation (Caus *et al.*, 1990). In the Terradets gorge section (El Montsec thrust sheet) the Boundary Breccia overlies unconformable Upper Jurassic dolostone and limestone (Fig. 2). At this locality, it is a massive, matrix-supported, up to 27m thick, breccia formed by angular clasts of dolostone and gypsum, probably eroded from the underlying succession (Fig. 4A-B). The matrix is a marine limestone (packstone) with benthic foraminifera. The Boundary Breccia at Terradets shows a general fining-upward trend, with clasts being up to 50–60cm across near the base and progressively decreasing in size to the top, where they barely reach 20cm across (Fig. 3). Laterally, this unit wedges and crops out irregularly along El Montsec Chain.

This unit was interpreted by Peybernès (1976) and Berástegui *et al.* (1995) as being related to the erosion of the exposed land and deposition of the resulting sediments in a marine setting. This process would have happened during the opening of the Upper Jurassic–Early Cretaceous rift in the Pyrenees. From the sedimentary point of view, the massive deposit, characterized by a fining-upward trend, matrix-supported fabric, and the marine fossil content within the matrix, suggests deposition resulting from a single high-density submarine debris flow event. The age of this unit includes the Jurassic–Cretaceous boundary (hence the name of Boundary Breccia) and varies from the Tithonian to the late Berriasian depending on the locality (Peybernès, 1976). In El Montsec thrust sheet, it may belong to the Berriasian *sensu lato* due to its stratigraphic position above Upper Jurassic dolostones and below the next unit, which is late Berriasian in age.

Trocholina and Dasycladaleans Limestone

The Boundary Breccia transitions upwards to a marine limestone rich in benthic foraminifera and dasycladales, up to 11.5m thick (Figs. 2; 3). This informal unit was characterized by Peybernès (1976) by the abundance of the foraminifera *Andersenolina alpina* (LEUPOLD) and *A. elongata* (LEUPOLD), formerly assigned to the genus *Trocholina* PAALZOW. The unit is widespread with similar facies throughout the Pyrenees, both in the northern and southern flanks of the mountain chain (Peybernès, 1976). For instance, in the Organyà Basin it has been defined as the Hostal Nou Formation (Berástegui *et al.*, 1995; García-Senz and Muñoz, 2019). However, in El Montsec the occurrence of this unit is discontinuous and it does not appear in the sections of La Pedrera de Meià and La Cabroa.

At Terradets, it displays two different facies, organized in meter-thick parasequences (Fig. 4). The lower part of the parasequence is a dark wackestone rich in benthic

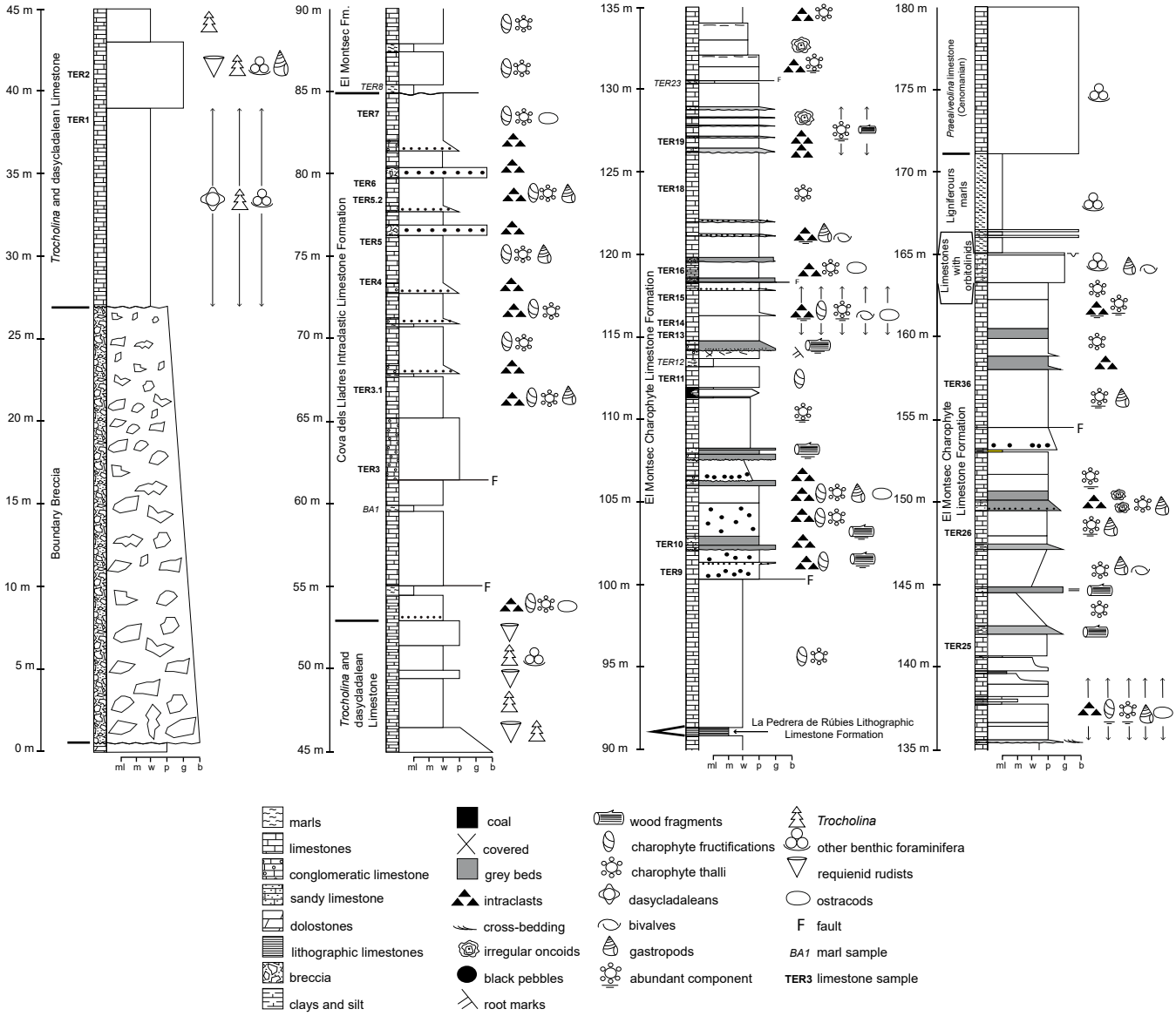

FIGURE 3. Stratigraphic section of the Lower Cretaceous in the Terradets gorge.

foraminifera (*Andersenolina*, miliolids) and dasycladales, some of them rounded or broken (Fig. 5), while the upper part is a packstone-grainstone rich in benthic foraminifera, requienid rudists and gastropods, also containing fragmented specimens (Fig. 4C). Four such parasequences have been recorded, becoming thinner to the top (Fig. 3). The rudist bed of the last parasequence shows an irregular, ferruginous top surface (Fig. 4D).

This unit is attributed here to sedimentation in a marine platform decreasing in depth to shallower coastal facies rich in requienid rudists. The last rudist bank was probably exposed and eroded before deposition of the overlying non-marine unit.

The *Trocholina* and Dasycladalean Limestone was attributed by Peybernès (1976) to the Late Berriasian based on the occurrence of *A. alpina, A. elongata,* and *Feurtilia frequens* MAYNC among other benthic foraminifera, and especially by the occurrence of very rare calpionellids in the lowermost beds, belonging to *Tintinnopsella* gr. *carpathica*.

Cova dels Lladres Intraclastic Limestone Formation

This unit is first proposed here with the rank of formation to include the lower part of the "Calcaires à Charophytes du Montsech" (informal unit N2) described by Peybernès (1976). It overlies the *Trocholina* and

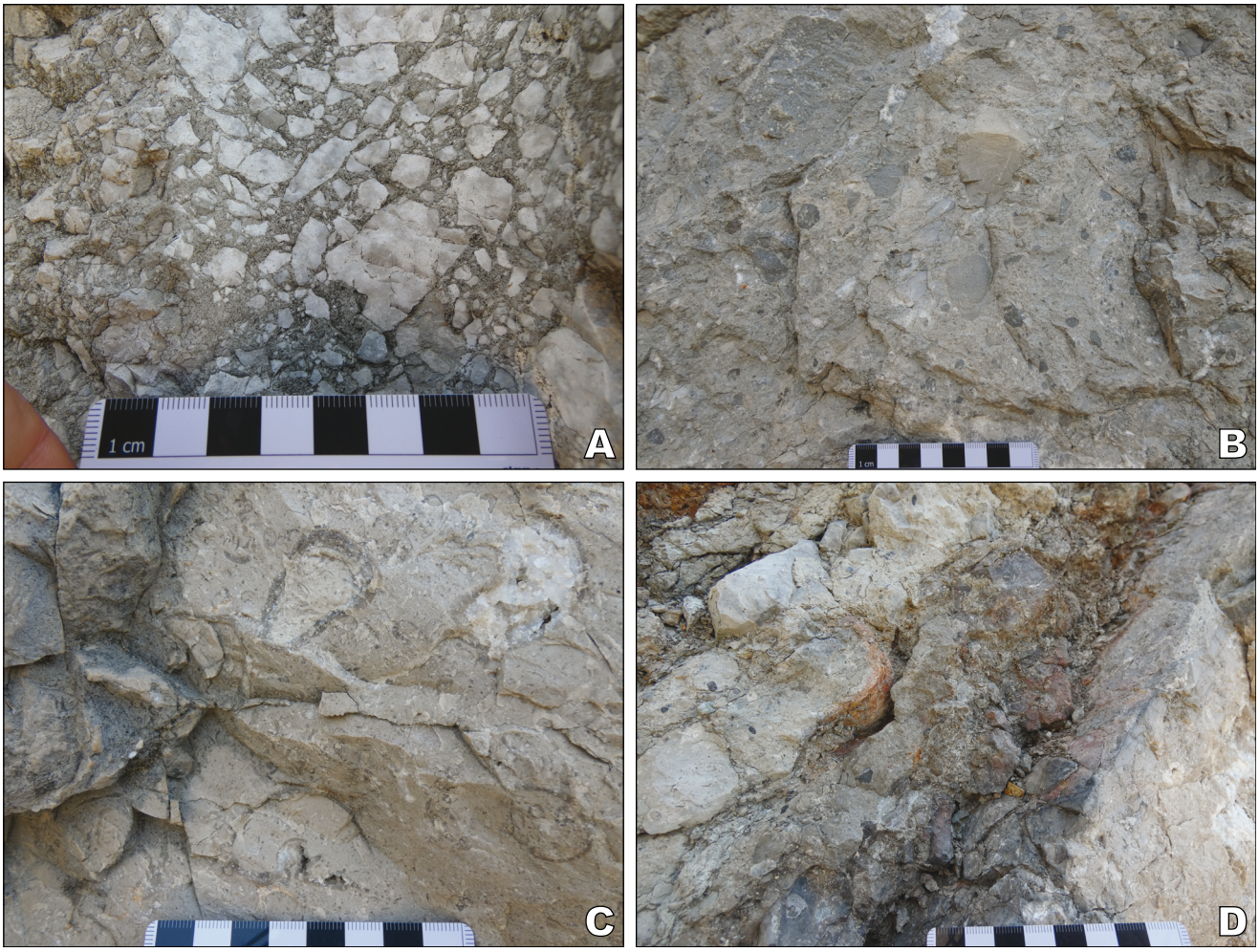

FIGURE 4. Outcrop views of the Boundary Breccia and the *Trocholina* and Dasycladalean Limestone in the Terradets gorge. A) Base of the Boundary Breccia. B) Top of the Boundary Breccia. C) Upper part of the *Trocholina* and Dasycladalean Limestone unit parasequences, showing abundant requienid rudists. D) Boundary between the *Trocholina* and Dasycladalean unit and the Cova dels Lladres Intraclastic Limestone Formation, showing a ferruginous surface.

Dasycladaleans Limestone (Fig. 2). The type section of the new formation, named after a nearby cave (meaning in Catalan, "the thieves' cave"), crops out along the C-13 road, south from La Font de les Bagasses parking area. Its base is located at 42º01'45.0"N and 00º52'59.67"E, coinciding with the last rudist-rich bed of the former unit. The top is located at 42º01'46.33"N, 00º52'59.0"E, coinciding with a well-marked angular unconformity and karstic surface.

The unit itself is made up of up to 32.5-m thick wackestone-packstone limestones rich in black-pebbles, charophytes and ostracods (Figs. 3; 6). Two main facies have been identified within this unit, alternating to form thinning-upward parasequences that are a few meters thick. The lower part of each parasequence is formed by packstone-limestones displaying an erosive base. It is easily recognizable in the field by the abundance of black intraclasts ("black pebbles"), which may be up to 15cm across, even resembling a conglomerate in the first parasequence at the base of the unit (Fig. 6). The top of the parasequences is formed by dark wackestone limestones rich in charophytes (well-preserved and articulated thalli and fructifications, mainly clavatoracean utricles), ostracods, gastropods (generally broken) and calcified cyanobacterial filaments of the *Cayeuxia* type (Fig. 7). Small lithoclasts may also occur. About eight such parasequences have been recorded in the 32.5m thick unit in the Terradets gorge (Fig. 3). They are asymmetrically distributed, with four larger, 3–6m thick parasequences at the base, and four smaller 1–3m thick, parasequences at the top.

The origin of this unit is attributed to sedimentation in a shallow freshwater lake that underwent repeated water table oscillations resulting in deepening-upward parasequences. These began with the exposure, mud-cracking and flooding of a previous lacustrine bed that lead to the deposition

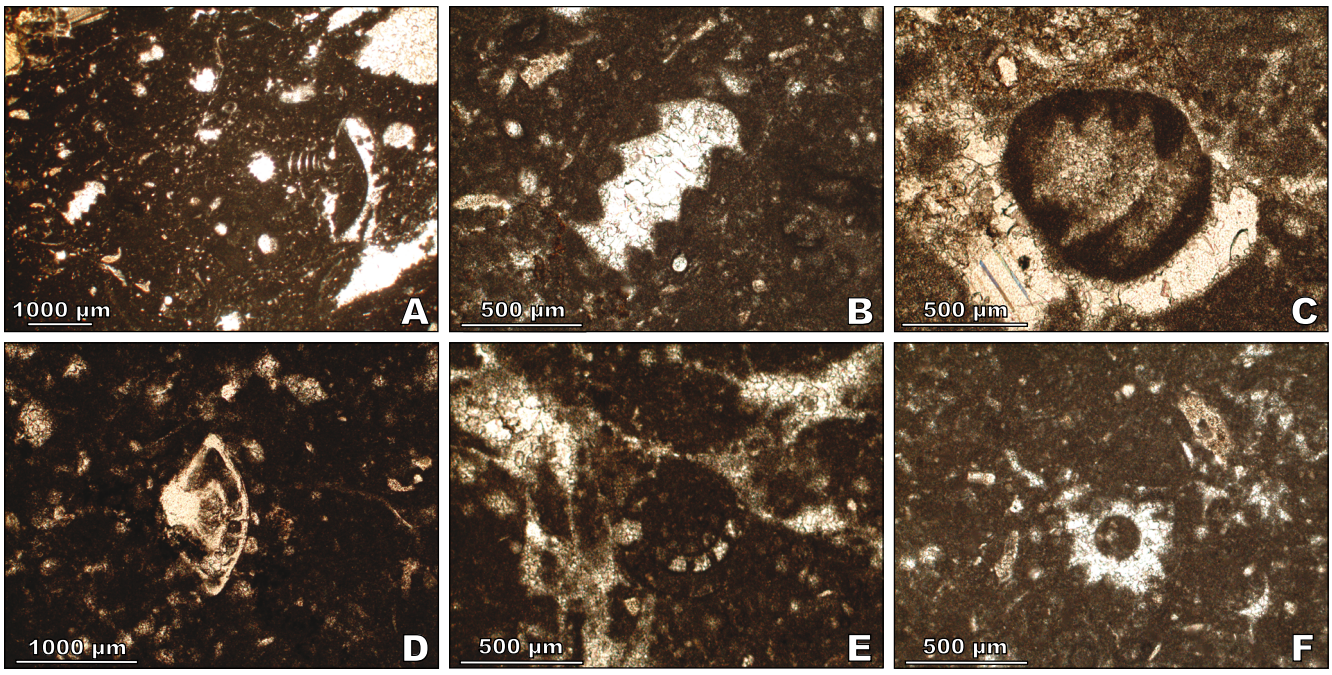

FIGURE 5. Skeletal components and microfacies of the *Trocholina* and Dasycladalean Limestone at Terradets (all from sample TER-1). A) Wackestone-packstone limestone belonging to the lower part of the parasequences of this formation showing abundant *Andersenolina* sp. foraminifera. B) Axial-tangential section of *Andersenolina elongata*. C) Axial-oblique section of *Andersenolina alpina*. D) Equatorial section of a planispiral involute hyaline benthic foraminifer. E) Axial section of a planispiral evolute hyaline benthic foraminifer. F) Transversal section of a dasycladalean thallus.

of the lake margin intraclasts. Sedimentation followed in a shallow permanent freshwater lake, where charophyte meadows were mainly dominated by clavatoraceans. The thickness of such parasequences decreases from the base to the top, suggesting a shortening in the duration of the climatic and/or tectonic factors controlling them.

The age of the Cova dels Lladres Intraclastic Limestone Formation has been determined as early Barremian based on the occurrence of *Atopochara trivolvis* var. *triquetra* GRAMBAST and *Ascidiella triquetra* (GRAMBAST) in one of the few marl beds of the succession. This assemblage belongs to the Globator maillardii trochiliscoides European biozone and to the Atopochara trivolvis triquetra Eurasian biozone of Pérez-Cano *et al.* (2022). To our knowledge, this unit only crops out near the Terradets gorge, since we have not found it at La Pedrera de Meià or La Cabroa outcrops.

El Montsec Charophyte Limestone Formation

This unit was first defined by Peybernès (1976) informally as "Calcaires à Charophytes du Montsech" and later assimilated to a formation by some authors (*e.g.* García-Senz and Muñoz, 2019). A new definition of this formation is proposed here, excluding its lower part, which is transferred to the new Cova dels Lladres Intraclastic Limestone Formation (Fig. 2). The Lithographic Limestone of La Pedrera de Rúbies Formation (also known by some authors as La Pedrera de Meià Formation) was originally defined by Peybernès (1976) as the informal unit "Calcaires lithographiques à plantes et ecimetre de la Pedrera de Rúbies", representing a lateral change of facies of El Montsec Charophyte Limestone Formation.

In the Terradets gorge section, El Montsec Charophyte Limestone Formation is up to 87.5m thick and includes near the base a 50cm thick bed belonging to La Pedrera de Rúbies Lithographic Limestone Formation (Figs. 3). The base of El Montsec Charophyte Limestone Formation in the Terradets gorge section is clearly marked by a prominent angular unconformity above the deeply karstified top of La Cova dels Lladres Intraclastic Limestone Formation (Fig. 8). The stratal angularity between the Cova dels Lladres Intraclastic Limestone Formation and the overlying El Montsec Charophyte Limestone Formation is highlighted by the dip directions of the strata, which differ up to 45º along the outcrop. The karst cavities, up to 3m deep, were filled in by onlapping beds of ferruginous marl and charophyte limestones. This specific karstic surface has not been identified at the base of El Montsec Charophyte Limestone Formation elsewhere, *i.e.* not at La Pedrera de Meià or La Cabroa outcrops.

El Montsec Charophyte Limestone Formation is made up of a repeated succession of meter-thick parasequences formed by three facies (Figs. 3; 9):

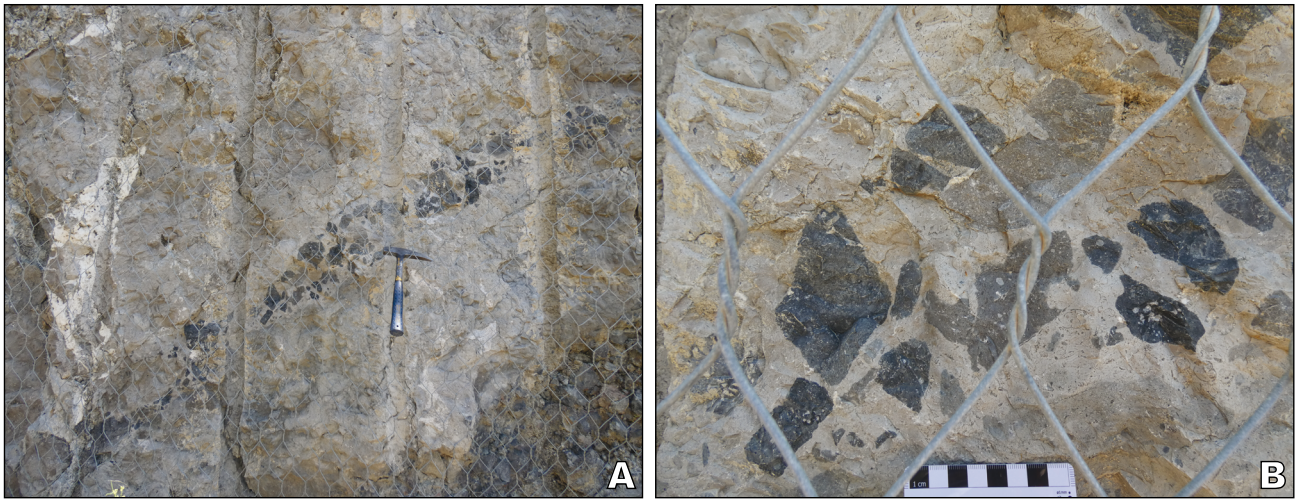

FIGURE 6. Outcrop views of the Cova dels Lladres Intraclastic Limestone Formation showing characteristic intraclastic limestones with abundant large black-pebbles. A) General view. B) Close-up view.

i) Carbonaceous limestone rich in lithoclasts and charcoal. This facies consists of thin-bedded layers, ranging from several centimeters to a few ecimetre in thickness, composed of dark-grey microconglomeratic limestone (Figs. 9A; 10). It is rich in organic matter with abundant charcoal fragments, rare small pieces of amber, lithoclasts, and small, barely determinable bioclasts (Figs. 10I, K). This facies is attributed to sedimentation in freshwater swamps or lake margins with an abundant supply of terrestrial remains. Abundant charcoal and amber suggest that its origin is related to erosion and deposition of the exposed deposits after a wildfire. The production of high amounts of amber during wildfires has been extensively documented in the Early Cretaceous worldwide (Delclòs *et al.*, 2023).

ii) Charophyte and oncoid packstone (Figs. 9B; 10). This is the best-developed facies. It is made up of decimetres- to meter-thick beds formed by grey packstone wackestone limestone rich in charophyte remains, including abundant thalli (*Clavatoraxis* sp., *Charaxis spicatus* MARTÍN-CLOSAS AND DIÉGUEZ) and clavatoracean utricles (Figs. 10A-G). Other skeletal remains include ostracod carapaces and gastropod shells. Microbial remains are also abundant, and they occur mainly as small oncoids, and cyanobacterial-like calcified filaments. The latter are isolated or clustered. Locally white intraclasts and small tube bioturbations measuring 1mm across also occur. This facies represents sedimentation in a shallow permanent freshwater lake rich in clavatoracean charophyte meadows (mainly *Echinochara* sp.) exposed to waves that would enhance the growth of oncoids.

iii) Mudstone with cyanobacterial filaments. This facies forms up to 2m thick beds and is poorly represented in the Terradets gorge succession. The skeletal components are calcified cyanobacterial filaments, sometimes organized in thickets (Fig. 10K), oncoids, small charophyte remains (thalli and clavatoracean utricles, mainly *Echinochara* sp. and *Atopochara* sp.), dasycladaleans, rare benthic foraminifera (miliolids and *Andersenolina* sp.) and gastropods. This facies has been attributed to sedimentation in a restricted brackish to euryhaline lagoon or coastal lake with both marine and non-marine influence.

These three facies are usually organized as fining-upward parasequences with facies a (carbonaceous limestone rich in lithoclasts and charcoal) transitioning upward to facies b (packstone rich in charophyte remains). Facies c is represented by mudstone with cyanobacterial filaments occurring at the top of some of these parasequences. This facies association is attributed to sedimentation in a shallow coastal permanent lake under a repeated deepening-upwards regime, perhaps climatically controlled. The occurrence of charcoal and abundant lithoclasts at the base of most parasequences suggests that the initial lake flooding ended periodic drier intervals associated with abundant wildfires.

El Montsec Charophyte Limestone Formation can be assigned to the upper part of the lower Barremian or lower part of the upper Barremian with the charophyte flora reported by Martín-Closas (1989, 2000) and Martín-Closas and López-Morón (1995, 1996) from the basal ferruginous marl at the Terradets gorge section and La Cabroa Konservat-Lagerstätten (Fig. 11). This flora belongs to the Hemiclavator neimongolensis neimongolensis Eurasian charophyte biozone of Pérez-Cano *et al.* (2022) and comprises *Porochara* gr. *kimmeridgensis* subgr. *kimmeridgensis* (MÄDLER), *Echinochara lazarii* (MARTÍN-CLOSAS), *Atopochara trivolvis* var. *triquetra* GRAMBAST, *Ascidiella triquetra* GRAMBAST and *Hemiclavator neimongolensis* var. *neimongolensis* WANG ET LU.

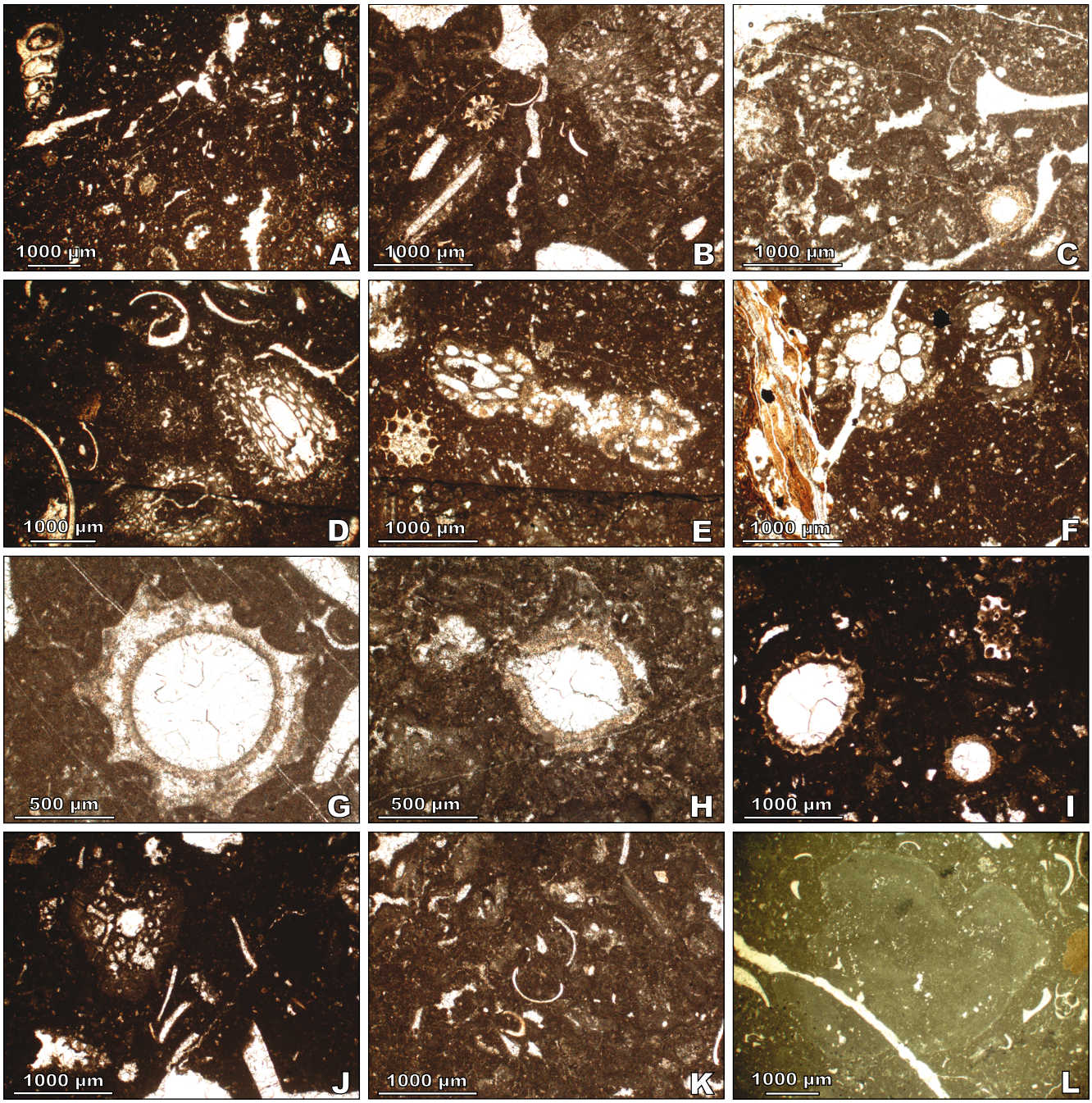

FIGURE 7. Skeletal components and microfacies of the Cova dels Lladres Intraclastic Limestone Formation at Terradets gorge (Samples TER-3 to TER-7). A) Wackestone-packstone texture with charophytes and gastropods. B) Close-up view of a cyanobacterial structure (upper-right portion of the image). C) Transversal section of *Charaxis spicatus*. D) Oblique section of *Charaxis spicatus*. Note also the presence of gastropod fragments. E) Oblique section of *Clavatoraxis* sp. portion. F) Transversal section of a *Clavatoraxis* sp thallus showing the cortical cells covered by spine-cell rosettes. G) Section of an atopocharoid utricle. H) Section of a clavatoroid utricle. I) Close-up view of a porocharacean gyrogonite. J) Possible cortoid with a section of *Palaeonitella* sp. K) Detail of ostracod carapaces (centre of the image). L) Close-up view of an intraclast.

Lower Cretaceous units overlying El Montsec Charophyte Limestone Formation

Above previous non-marine deposits the sedimentation became mainly marine and is formed by Urgonian type limestones rich in orbitolinid foraminifera. This unit is poorly developed in the Terradets gorge section, where it is only represented by a 2m thick bed of a foraminifer-rich grainstone overlying El Montsec Charophyte Limestone Formation. However, it crops out more extensively to the east (*e.g.* Mina del Montsec near El Reguer ravine, Montsec de Rúbies) or to the west (*e.g.* L'Ametlla, Montsec

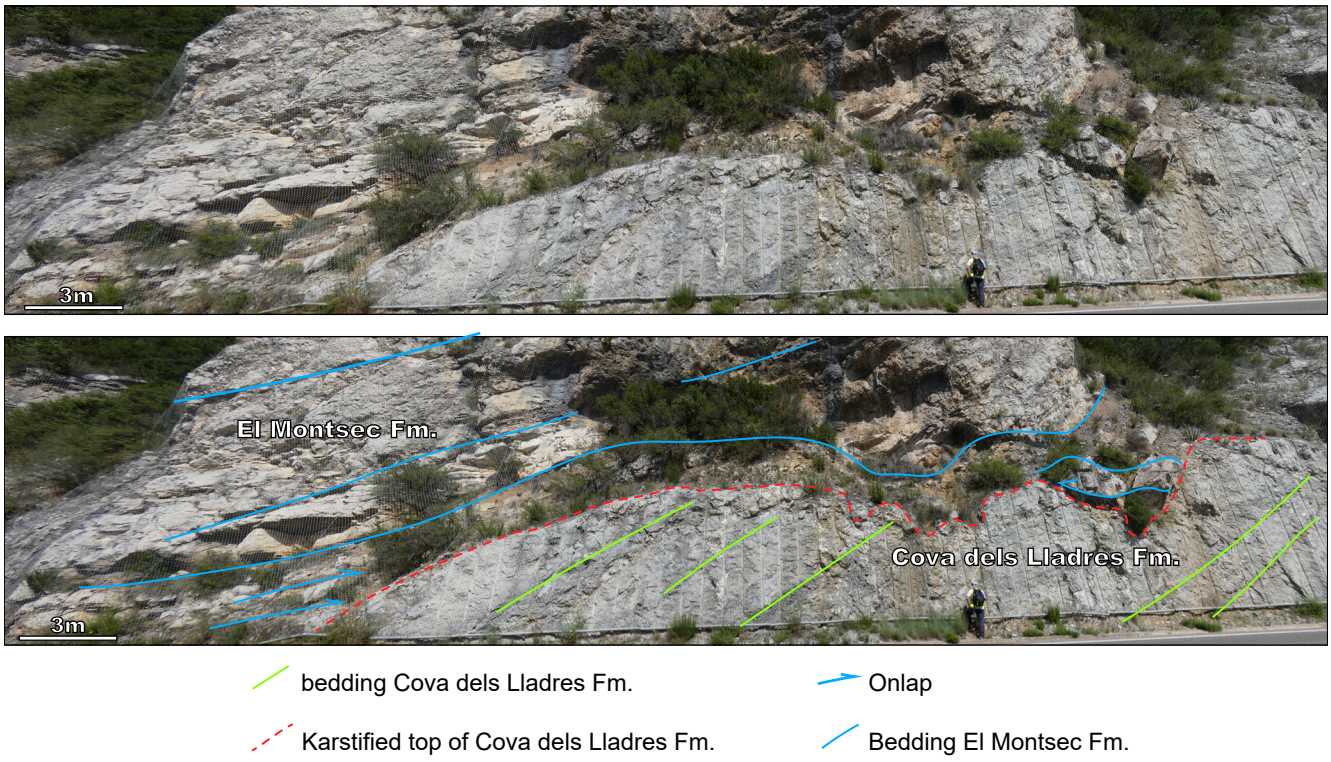

FIGURE 8. Angular unconformity and karst surface between the Cova de Lladres Intraclastic Limestone Formation and El Montsec Charophyte Limestone Formation at Terradets gorge. A) Field view. B) Interpretation.

d'Ares). The age of these marine limestones has been a matter of debate. West of Terradets, near l'Ametlla (Montsec d'Ares), the base of this unit directly overlies El Montsec Charophyte Limestone Formation and has been attributed to the late Barremian based on a rich assemblage of benthic foraminifera. This assemblage contains *Valserina brunnimanni* SCHROEDER ET CONRAD, *Palaeodictyoconus cuvillieri* (FOURY), *Eopalorbitolina* cf. *charollaisi* SCHROEDER ET CONRAD and *Urgonina alpillensis* (FOURY) among others (Schroeder *et al.*, 1982). However, in El Montsec de Rúbies, near the abandoned lignite mine of El Montsec (El Reguer ravine), Peybernès (1976) attributed them to the early Aptian based on the occurrence of *Simplorbitolina praesimplex* (SCHROEDER), *Orbitolinopsis flandrini flandrini* BASSOULET ET MOULLADE and *Paracoskinolina sunnilandensis* (MAYNC), among others.

The last unit of the Lower Cretaceous from El Montsec thrust sheet is represented by marls, sandstone and locally lignite, included in unit M2b of Peybernès (1976) "Marnes et manocalcaires ligniteux à Pseudochoffatelles". These were also named "Montsec lignitiferous marls" by García-Senz and Muñoz (2019). In the Terradets gorge section this unit is only 6m thick and is formed by yellowish marls and sandstone underlying the characteristic Cenomanian *Praealvelina* limestone. This unit can be attributed to sedimentation in a transitional deltaic or estuarine system. Peybernès (1976) provided the only available biostratigraphic markers of this unit, comprising palynomorphs, brackish ostracodes and clavatoracean charophytes found in clay intercalated with lignite at Mina del Montsec (El Reguer ravine, Montsec de Rúbies), which he attributed to the late Aptian. The charophyte species *Clavator harrisii* var. *zavialensis* GRAMBAST-FESSARD (reported as *Flabellochara* sp. by Peybernès, 1976) was found forming homogeneous populations in the assemblage, which is characteristic of the late Aptian–early Albian (Grambast-Fessard, 1980; Martín-Closas, 1996, 2000). This type of assemblages is common in the early Albian Escucha Formation of the Iberian Chain (*e.g.* Álvarez-Parra *et al.*, 2021; Tibert *et al.*, 2013). The Montsec lignitiferous marls are covered by the Cenomanian *Praealveolina*-rich limestones.

DISCUSSION

The non-marine stratigraphic record of the Lower Cretaceous at El Montsec thrust sheet, which was traditionally included in the El Montsec Charophyte Limestone Formation is here subdivided into two units of different ages separated by an angular unconformity and

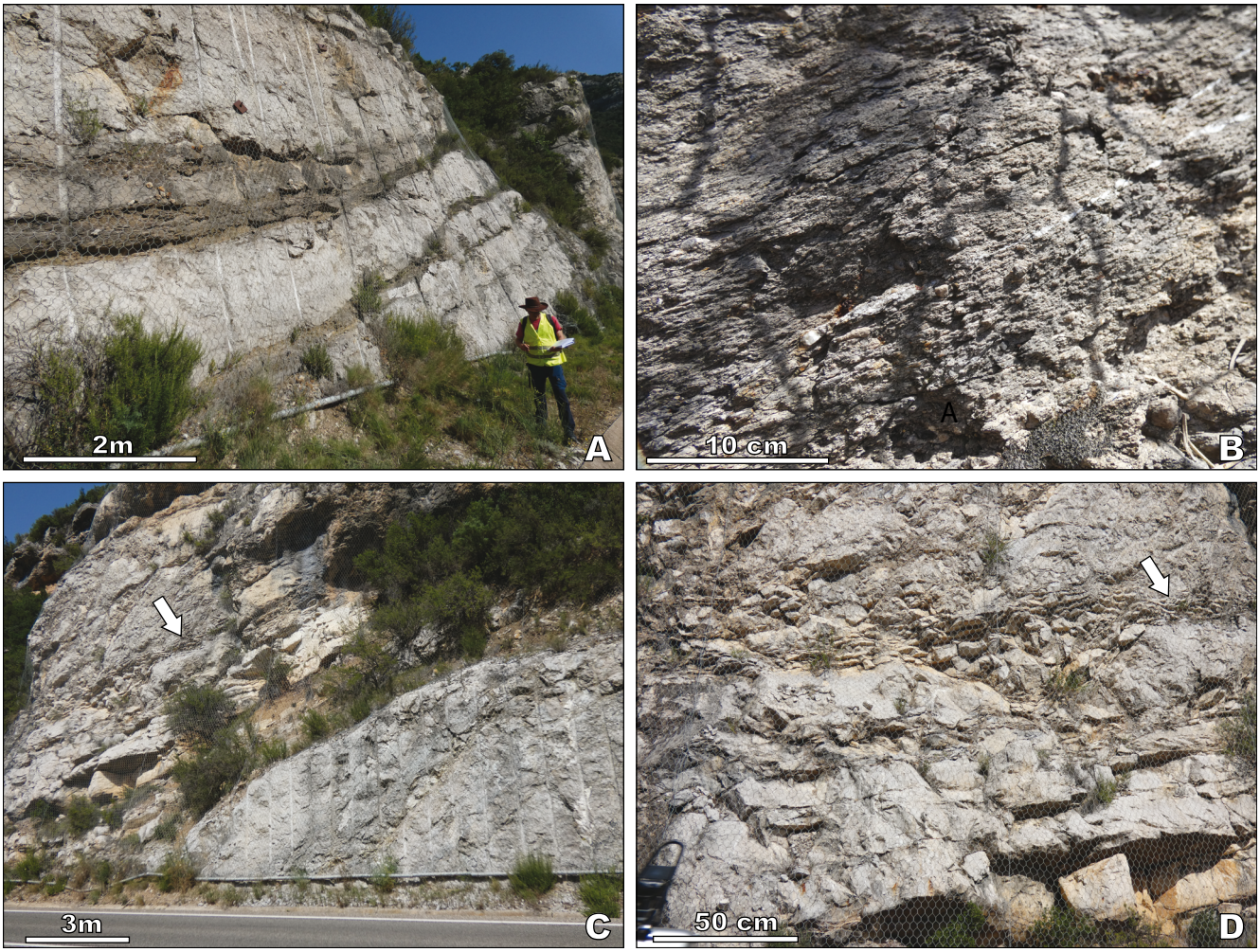

FIGURE 9. Outcrop views of El Montsec Charophyte Limestone Formation at Terradets gorge. A) Alternation of charophyte limestones (light grey beds) and grainstone limestones rich in charcoal (dark grey beds). B) Detail of a grey bed showing the microconglomerate texture with coal remains. C–D) Outcrop views of a thin interval of lithographic limestone (arrow) belonging to the Pedrera de Rúbies Lithographic Limestone Formation.

a karstic surface (Fig. 12): i) the new Cova dels Lladres Intraclastic Limestone Formation at the base, attributed to the early Barremian and ii) the redefined El Montsec Charophyte Limestone Formation at the top, restricted here to the charophyte limestones located above the discontinuity, and newly attributed to the early to late Barremian boundary ('middle' Barremian). The Pedrera de Rúbies Lithographic Limestone Formation represents a lateral change of facies from the upper unit exclusively, *i.e.* 'middle' Barremian in age.

The new results allow the age of the stratigraphic gap existing between the marine and the non-marine Lower Cretaceous units at the Terradets gorge to be refined, comprising at least the Valanginian and the Hauterivian (Fig. 12). In addition, the angular unconformity separating the two Barremian non-marine units represents an intra-Barremian gap. These units are clearly distinguished from each other by biostratigraphic and sedimentological features attesting to different sedimentary and palaeoenvironmental origins.

The new lower Barremian Cova dels Lladres Intraclastic Limestone Formation is only recorded in the Terradets gorge, disappearing both to the west (*e.g.* El Montsec d'Ares) or the east (*e.g.* at La Pedrera de Meià and La Cabroa outcrops), where the "middle" Barremian El Montsec Charophyte Limestone Formation directly overlies the Jurassic dolostone, at La Pedrera de Meià, or the Boundary Breccia at La Cabroa (Fig. 12). In La Pedrera de Meià outcrop the unconformity underlaying El Montsec Charophyte Limestone Formation represents an important karst (Gil-Delgado *et al.*, 2023b), which contains a stratigraphic gap representing the addition of the unconformity at the base of El Montsec Charophyte Limestone Formation with the unconformity at the base of the Boundary Breccia (Fig. 12).

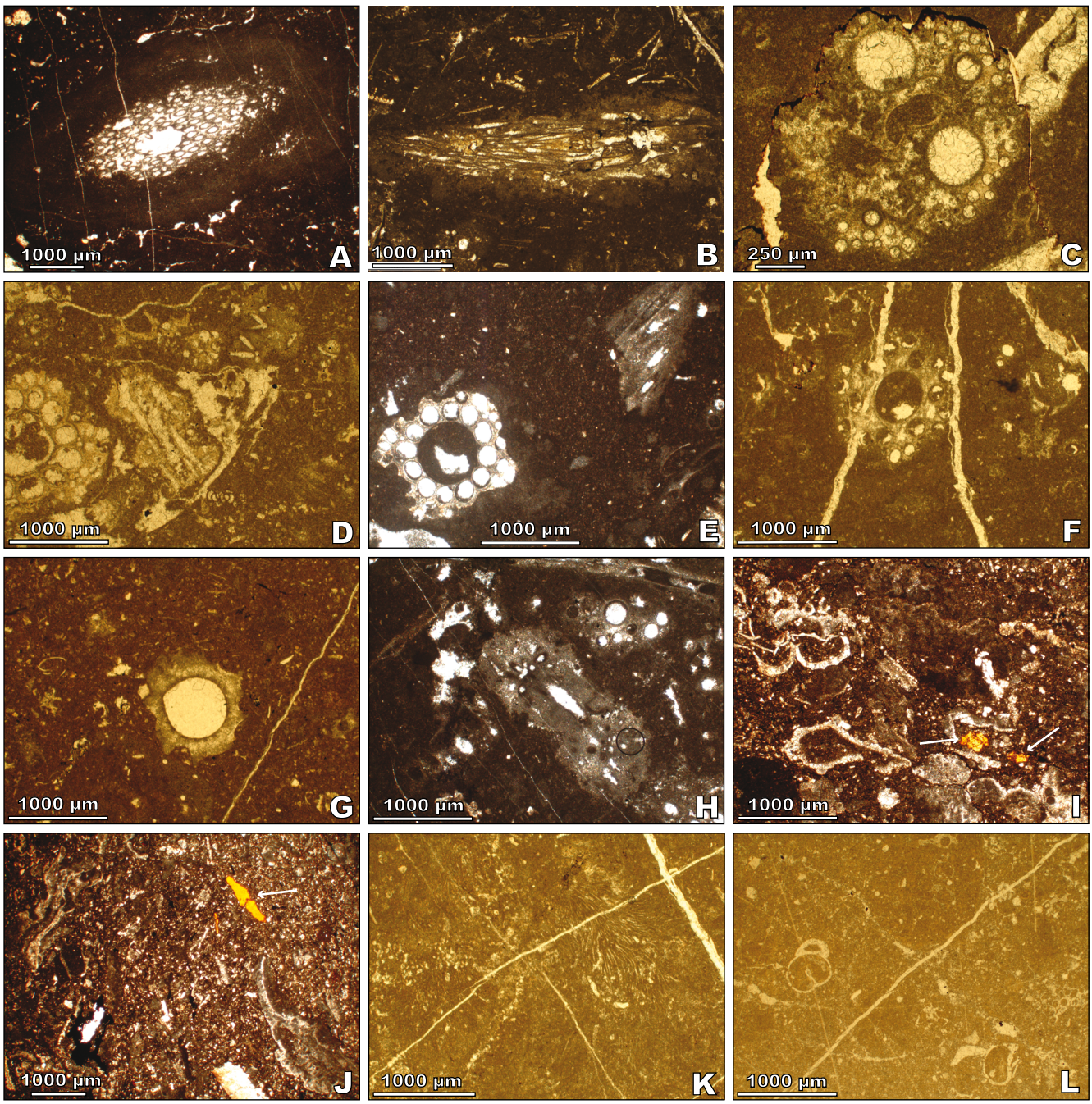

FIGURE 10. Skeletal components and microfacies of El Montsec Charophyte Limestone Formation at Terradets gorge (Samples TER-9 to TER-36). A) Oncoid with a portion of *Charaxis spicatus*. B) Longitudinal section of *Charaxis spicatus*. C) Fertile whorl of *Echinochara* sp. showing two well-preserved utricles D) Charophyte limestone with a transversal section of *Clavatoraxis* sp. E) Transversal section of *Clavatoraxis* sp. F) Transversal section of a *Charaxis* sp. G) atopocharoid utricle. H) Longitudinal section of a cortoid with a *Palaeonitella* sp. I) Clastic microfacies containing amber (arrows). J) Clastic microfacies containing amber (arrows). K) Clustered cyanobacterial filaments. L) Wackestone limestone containing gastropods and ostracods.

The occurrence of a Barremian unit above a Berriasian unit (sometimes including the lowermost Valanginian) or even above older units is not exclusive to El Montsec thrust sheet. On the contrary, it has been recorded in several basins of the Iberian plate, always in the basin margins.

In the Pyrenean Organyà Basin (Bóixols thrust sheet) the Tres Ponts gorge section shows the lower Barremian shallow marine Prada Formation directly overlying the lower Valanginian deposits of the Hostal Nou Formation (Berástegui *et al.*, 1995; García-Senz and Muñoz, 2019). In the Catalan Coastal Chain (La Pleta de Garraf section)

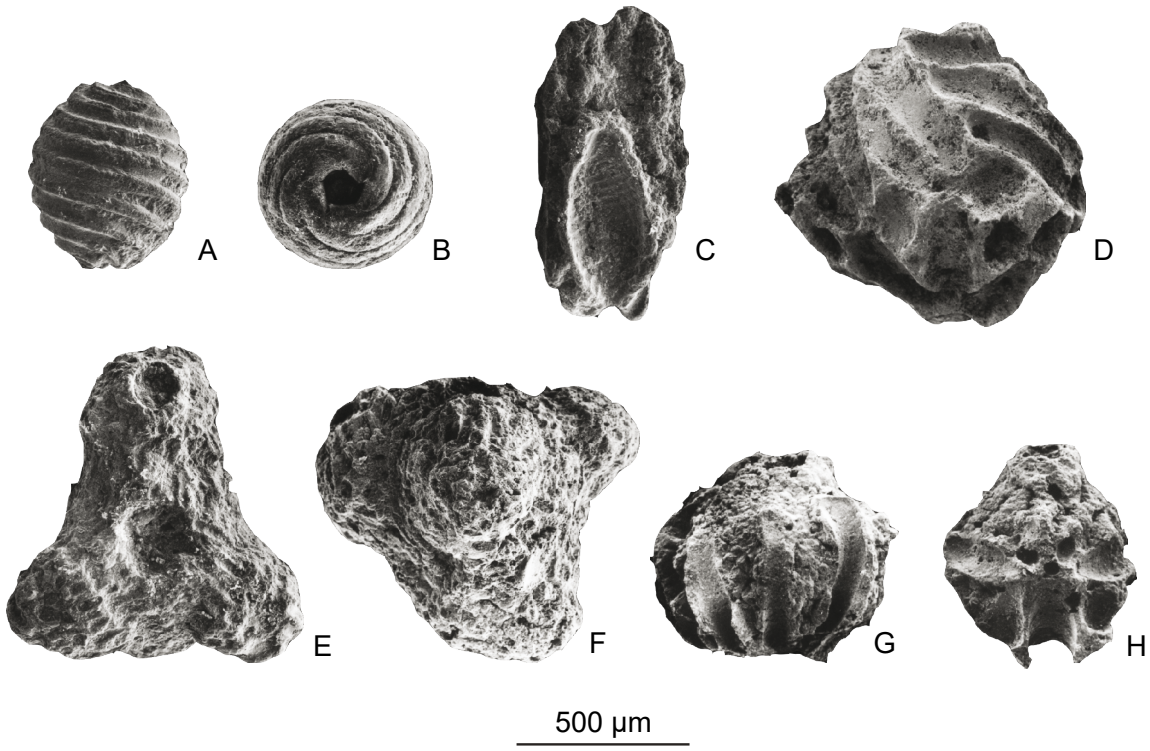

FIGURE 11. Charophyte fructifications found at the base of El Montsec Charophyte Limestone Formation (sample TER-8). A–B) *Porochara* gr. *fusca*. B) *Echinochara lazarii*. D) *Atopochara trivolvis* var. *triquetra*. E–F) *Ascidiella triquetra*. G–H) *Hemiclavator neimongolensis* var. *neimongolensis*.

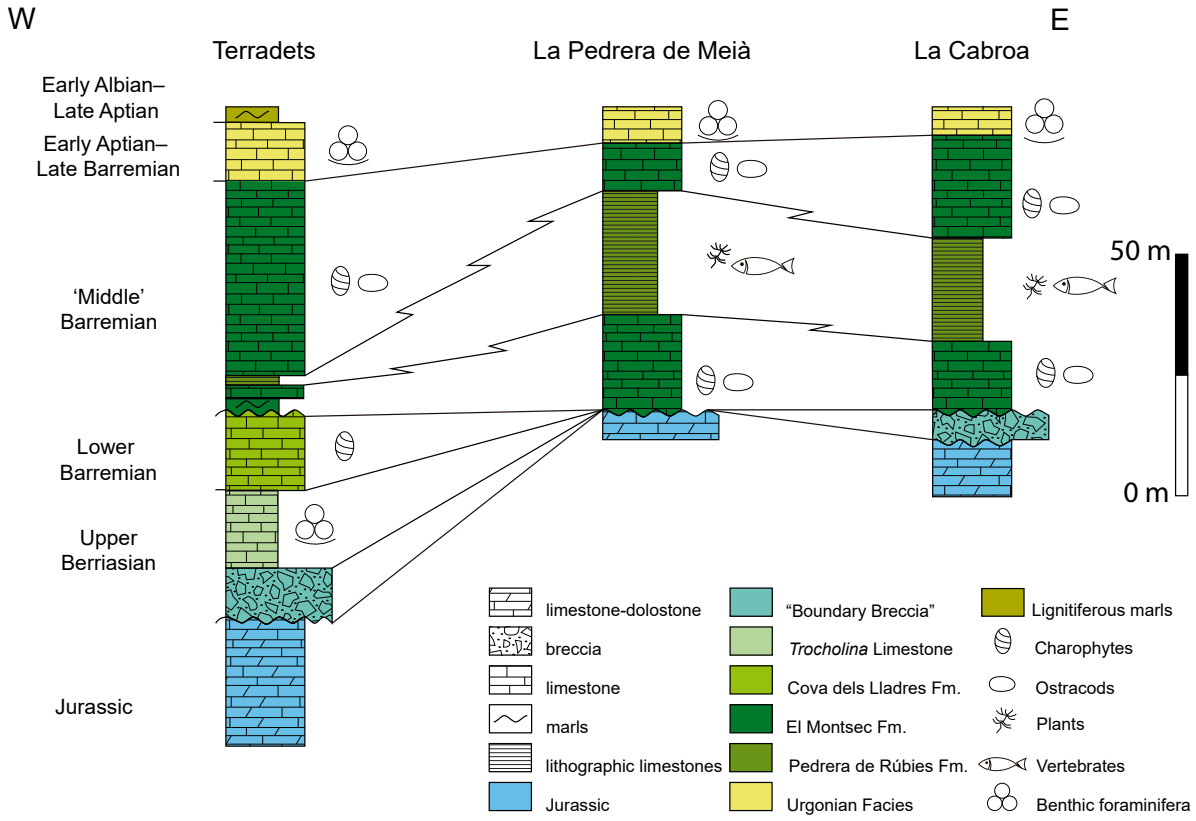

FIGURE 12. Stratigraphic correlation chart of the non-marine Barremian lithostratigraphic units in El Montsec thrust-sheet, showing the Terradets gorge section (studied herein), La Pedrera de Meià outcrop and La Cabroa outcrop.

the Barremian non-marine to transitional Cantaperdius Formation directly overlies the shallow marine lowermost Valanginian Polacos Formation (Albrich *et al.*, 2006). The Iberian Chain offers several examples of the same stratigraphic situation, with the deposits of the first Barremian Sedimentary Sequence K.1.4, overlying Upper Jurassic to lowermost Cretaceous deposits of sequences J10 or K1.1. respectively (Salas *et al.*, 2001; Salas *et al.*, 2019). This is common for instance in the northern margin of the Maestrat Basin (Morella subbasin), where the lower Barremian non-marine Cantaperdius Formation directly overlies the tidalites of the Tithonian–Berriasian La Pleta Formation (Martín-Closas and Salas, 1994; Salas *et al.*, 1995). In the Maestrat Basin and elsewhere in the Iberian Chain the non-marine Barremian may overlie much older stratigraphic units belonging to the entire Jurassic and even to the Triassic (Salas *et al.*, 2001), for instance at Las Hoyas, in the Serranía de Cuenca (Cuenca province, central Spain), the upper Barremian non-marine La Huérguina Formation overlies deeply karstified Middle Jurassic limestones and dolostones (Fregenal-Martínez *et al.*, 2017). This is also frequent in other basin margins outside the Iberian Chain or the Pyrenees, for instance in the Algarve basin in the Arrifes section (South Portugal), where the uppermost Hauterivian–lower Barremian non-marine formations directly overlie the marine lower Valanginian Porches Formation (Pérez-Cano *et al.*, 2023). Also, in the Cantabrian basin (North Spain), the lower Barremian non-marine Vega del Pas Formation has been found to directly overlie the uppermost Triassic–Lower Jurassic "Carniolas" unit (Trabelsi *et al.*, 2024 and references therein).

The occurrence in the whole Iberian plate of a very well-represented Barremian record, usually in non-marine facies, directly overlying all previous Mesozoic units, has been attributed to an acceleration of the tectonic subsidence during the Mesozoic rift (Salas *et al.*, 2001; Salas *et al.*, 2019). Indeed, Tugend *et al.* (2015) linked this generalized increase in the Iberian tectonic subsidence to the opening of the Bay of Biscay.

At El Montsec thrust sheet, this syn-rift tectonics is well characterized by the occurrence of an angular unconformity formed during the early Barremian exclusively. An intra-Barremian angular unconformity was reported by Meléndez Hevia (1982) to also occur at La Serranía de Cuenca (southwestern Iberian Chain). However, in Terradets this discontinuity can be well-characterized biostratigraphically and is better visualized at the outcrop scale than in previous reports. In other basins of the Iberian Chain, although different Barremian units are also separated by unconformities (Salas *et al.*, 2001), no angularity has been noticed between them. For instance, in the north-eastern margins of the Maestrat Basin, up to four laterites associated with stratigraphic gaps were reported within the non-marine Barremian (Combes, 1969).

CONCLUSIONS

The non-marine Lower Cretaceous of El Montsec thrust sheet (south-central Pyrenees), generally considered to be an isochronous charophyte limestone (formerly Berriasian–lower Valanginian and more recently lower Barremian in age) is subdivided here into two units, respectively of early Barremian and 'middle' Barremian age. They are separated by an angular unconformity exhibiting a well-developed karst surface and a stratigraphic gap comprising part of the lower Barremian. These Barremian units overlie upper Berriasian or Jurassic marine units.

This result clarifies the stratigraphy of the Lower Cretaceous of El Montsec thrust sheet, which has frequently been put aside by comparison with the better-known record of the Organyà basin (Bóixols thrust sheet). A similar stratigraphic situation, with Barremian units overlying much older Mesozoic units, has been repeatedly characterized in many parts of the Iberian plate. These have been associated with a phase of acceleration in the tectonic subsidence of the Iberian Mesozoic rift, coeval with, and resulting from, the opening of the Bay of Biscay. At the Terradets gorge (El Montsec thrust sheet) this situation is well-characterized by the occurrence of an intra-Barremian angular unconformity, which is well-dated and visible at the outcrop scale.

The main implications of our results are: i) the non-marine Lower Cretaceous record of El Montsec is formed by two Barremian units (the Cova dels Lladres Intraclastic Limestone Formation and El Montsec Charophyte Limestone Formation) separated by an angular unconformity, resolving uncertainties about its age and stratigraphic composition. ii) The Pedrera de Rúbies Lithographic Limestone Formation containing an exceptionally well-preserved paleontological record (La Pedrera de Meià and La Cabroa Konservat-Lagerstätten), is now constrained in age to the 'middle' Barremian (*i.e.* late early Barremian to early late Barremian) Hemiclavator neimongolensis neimongolensis Eurasian charophyte biozone.

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