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*Depositional conditions of carbonate-dominated palustrine sedimentation around the K-T boundary (*Faciès Rognacien, *northeastern Pyrenean foreland, southwestern France)*

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ABSTRACT

The *Faciès Rognacien* is a sequence of highly bioturbated and pedogenically modified palustrine carbonates that were deposited under oxic conditions around the Cretaceous-Tertiary (K-T) boundary in the northeastern Pyrenean foreland basin (SW France). The sedimentary structures and early diagenetic features identified (mottling, nodule formation, brecciation, pseudomicrokarst, cracking, charophytes, *Microcodium*) suggest deposition in a palustrine environment between the subarid and intermediate climate type. Sedimentological and paleoecological analysis enables us to distinguish two facies associations, the lacustrine pond facies and the freshwater marsh facies associations. The majority of the carbonates are attributed to the freshwater marsh facies. The lacustrine pond facies occurs only in isolated paleolows, and is identified on the basis of its paleobiological content (charophytes, ostracodes). This suggests that the palustrine carbonates of the *Faciès Rognacien* were deposited in a seasonal wetland (carbonate-producing freshwater marsh), rather than in the marginal zone of a large, shallow lake. In this wetland paleoenvironment, all carbonates underwent widespread pedogenesis, and small, ephemeral ponds are of limited distribution, most likely recording deposition in paleolows.

Keywords: palustrine carbonates, seasonal wetland, freshwater marsh, Rognacien, K-T boundary, SW France.

RESUMEN

La *Faciès Rognacien* es una secuencia formada por carbonatos palustres muy bioturbados y modificados pedogénicamente, que se depositó bajo condiciones óxicas en la cuenca de antepaís Pirenaica (SW de Francia). Su edad está entorno al límite K-T. Las estructuras sedimentarias y los rasgos diagenéticos tempranos (caráceas, *Microcodium*, moteado, formación de nódulos, brechificación, pseudomicrokarst, fisuración) indican que esta secuencia se depositó en un ambiente palustre de clima

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subárido a intermedio. Los análisis sedimentológicos y paleontológicos permiten distinguir dos asociaciones de facies: charcas lacustres y zonas pantanosas de agua dulce. Las facies de charcas aparecen aisladas en paleodepresiones y tienen un contenido paleobiológico característico (caráceas, ostrácodos). Esto sugiere que los carbonatos palustres de esta secuencia se depositaron en humedales estacionales más que en las zonas marginales de grandes lagos someros. En estos humedales todos los carbonatos sufrieron modificaciones pedogénicas importantes.

Palabras clave: carbonatos palustres, humedales estacionales, pantanos de agua dulce, Rognaciense, límite K-T, SW de Francia.

INTRODUCTION

Freytet (1971a, 1971b, 1973, and 1984) and Freytet and Plaziat (1982) provided good overviews of the continental deposits of southern France, including exhaustive descriptions of palustrine sedimentological features. More recently, other authors have described palustrine carbonates from the Cretaceous and Tertiary of France and Spain (e.g., Platt, 1989a; Cojan, 1999) or provided reviews on palustrine carbonates (e.g., Platt and Wright, 1991; Armenteros et al., 1997; Alonso-Zarza 2003). Palustrine facies have only been recognized and studied during the last thirty years (Wright and Platt, 1995), and much less is known about them than about marine carbonates (Alonso-Zarza, 2003). Nevertheless, palustrine sequences are now known from the Carboniferous to the Neogene (Wright and Platt, 1995), mostly within continental successions and intercalated with floodplain deposits.

It was Freytet (1964) who introduced the term palustrine (Latin: "paluster" = swampy, marshy), and Freytet (1984, p. 231) presented the following definition: "A palustrine limestone exhibits systematically characteristic features of the primary lacustrine deposit (organisms, sedimentological features), as well as features due to later transformations (organisms, root traces, desiccation, pedologic remobilisations)." The term palustrine is commonly applied as a nonmarine equivalent for peritidal. Freytet and Plaziat (1982) interpreted their palustrine facies as marginal lake deposits of shallow, unstratified freshwater lakes with swampy surroundings. Platt and Wright (1991, 1992) and Wright and Platt (1995) expanded on these ideas, noting that low shoreline gradients led to the extensive exposure of lake margins at times of low water level, and that many ancient palustrine successions show a dominance of pedogenically modified carbonates over those recording a primary lacustrine origin. Their analogy with modern environments of the Florida Everglades suggested that palustrine carbonates are the products of hardwater seasonal wetlands (sensu Tarnocai, 1979).

Wetlands, however, are intermediaries between terrestrial and aquatic (lacustrine) ecosystems, and palustrine environments are often studied in combination with other depositional systems, such as lakes, deltas, or floodplains, rather than being treated as a distinct entity (Liutkus and Ashley, 2003). Hence, no sedimentological facies models have been developed as yet for freshwater wetlands, as they have for other depositional environments (Liutkus and Ashley, 2003). Consequently, there is a limited understanding of their origin, how they are sustained hydrologically, and the type of sedimentary deposit that may be preserved in the geological record (Ashley et al., 2004). Only recently, following the model of Wright and Platt (1995), Flügel (2004, p. 13 and p. 742) provided a revised definition of the palustrine facies as pedogenically modified carbonates of nearshore deposits of extremely shallow lakes with oscillating water level and densely vegetated shorelines, as well as of carbonate swamps surrounding these lakes.

This paper analyzes facies within the palustrine carbonates of the *Faciès Rognacien* (Cretaceous-Tertiary [K-T] boundary) of SW France, and reconstructs the paleoenvironment in detail. Within the research area, all carbonates of the *Faciès Rognacien* are pedogenically modified and can be classified as palustrine carbonates. However, carbonates clearly exhibiting evidence for a primary lacustrine origin are very scarce and occur only in isolated locations. These carbonates are described as the lacustrine pond facies association, as it is inferred that they were formed in small and ephemeral ponds. The majority of the carbonates of the *Faciès Rognacien* does not show any evidence of a primary lacustrine origin, and are thus attributed to the freshwater marsh facies association. This observed facies distribution pattern cannot be well explained with the "marginal lake" facies model of Freytet and Plaziat (1982), or the marginal lacustrine facies of Platt and Wright (1991), respectively. Moreover, this makes clear the assertion that the palustrine carbonates of the *Faciès Rognacien* precipitated in freshwater marshes within a carbonate wetland environment. This paper describes the lithofacies associations of both the freshwater marsh and the lacustrine pond facies, proposes microfacies and paleontological criteria for their recognition, and reconstructs the ancient wetland environment of the *Faciès Rognacien* in great detail.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The study area is situated in the folded northern Pyrenean foreland (southwestern France, Département Aude), which is separated from the North Pyrenean zone to the south by the North Pyrenean frontal thrust and from the North Aquitaine folded foreland to the north by the sub-Pyrenean frontal thrust (Bousquet, 1997; Charrière and Durand-Delga, 2004) (Fig. 1).

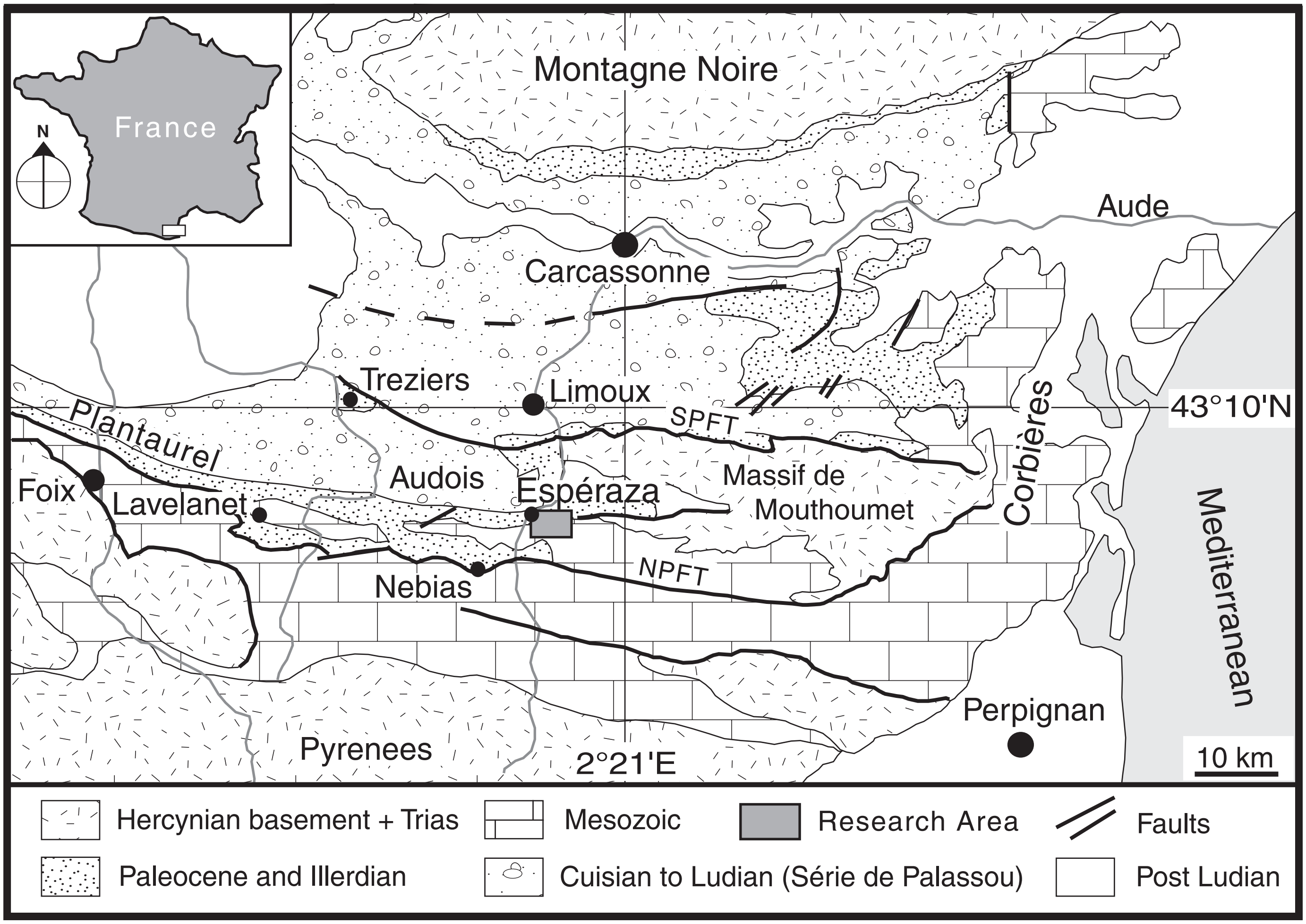


Figure 1. Geographical and geological setting of the research area. NPFT—North Pyrenean frontal thrust, SPFT—sub-Pyrenean frontal thrust (after Tambareau et al. [1995, 1997] and Bousquet [1997]).

A progressive and complex regression occurred across the Pyrenean area during the Cretaceous (Bilotte, 1978; Bilotte et al., 1983; Babinot et al., 1983). The orogenesis of the Pyrenees started between Late Cretaceous and Early Tertiary times (Bousquet, 1997). Erosion and continental sedimentation were widespread throughout much of the Pyrenean foreland from the Early Campanian until the Early Thanetian (Fig. 2). Within the research area, the basin was tectonically bounded to the north by the Montagne Noire Massif and to the south by the rising Pyrenean Range (Tambareau et al., 1995) (Fig. 1).

The best overviews of the regional geology and paleontology are those by Freytet (1970, 1971a), Jaffrezo (1977), Plaziat (1981, 1984), Bilotte et al. (1989), Bousquet (1997), and Bousquet and Vianey-Liaud (2001). The text booklet of the geological map of Quillan (Bessière et al., 1989) provides a short lithological description of the *Faciès Rognacien*, but to date, only Peybernès and Combes (1999) have examined the *Faciès Rognacien* of the study area in greater detail.

STRATIGRAPHY

Generally, the terms Rognacien and Vitrollien serve as local lithostratigraphic units in southern France (Provence) for the continental units of Late Cretaceous and Early Danian age, respectively (Babinot and Durand, 1980; Babinot et al., 1983). The "Rognacien" was introduced in Villot (1883) using Rognac near Aix-en-Provence (Provence) as the type locality (Babinot and Durand, 1980). In lithofacies terms, the Rognacien is characterized by an intimate association of lacustrine and palustrine marls and limestones with various types of "hypercalcimorph" soils (Freytet and Plaziat, 1982; Babinot et al., 1983). The lithostratigraphic units Rognacien and Vitrollien have also been used in a chronostratigraphic sense in Languedoc and the Pyrenees (Freytet, 1970; Plaziat, 1970; Bilotte, 1978), which are located far away, however, from the type locality. Thus, and in order to avoid confusion, we use the terms *Faciès Rognacien* and *Faciès Vitrollien*, respectively (following Bessière et al., 1989; Fig. 2).

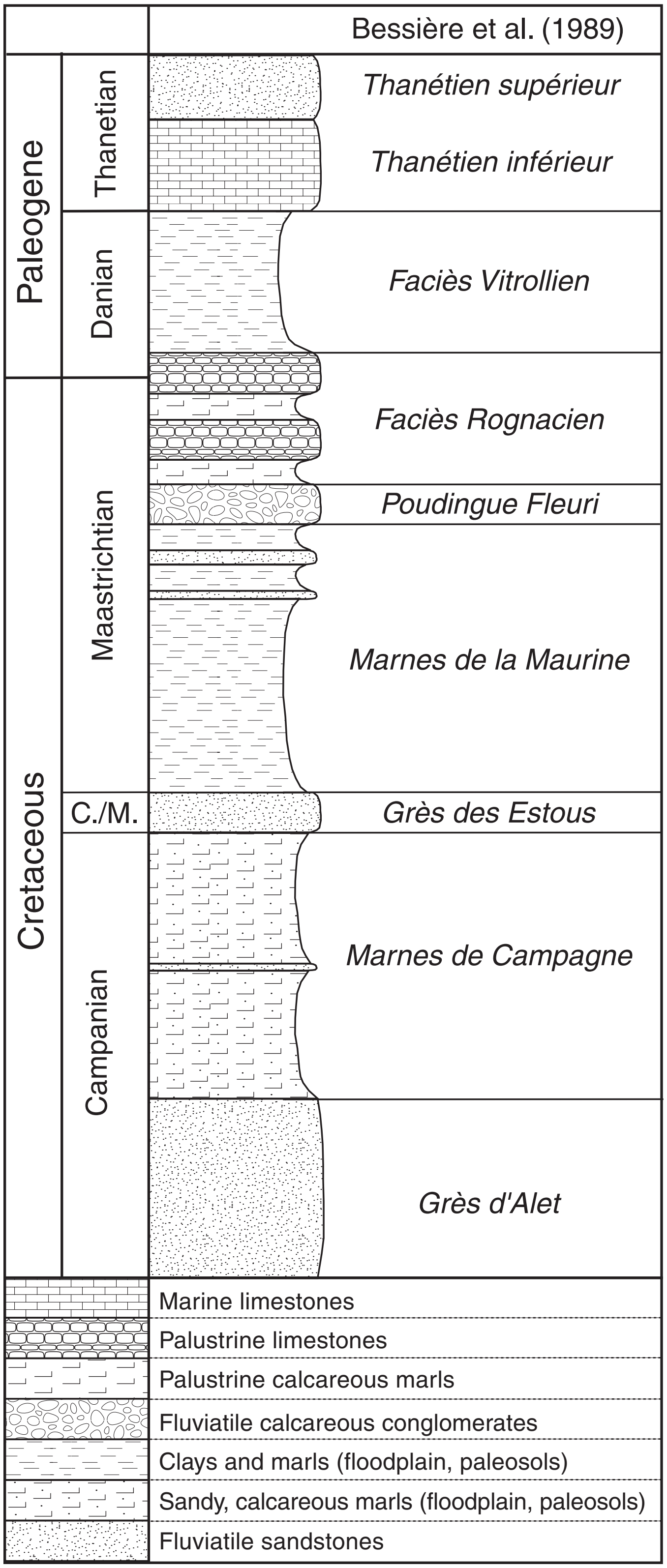


Figure 2. Generalized stratigraphic framework from the Campanian to the early Danian for the research area (not to scale; after Bessière et al., 1989). Based on charophyte biostratigraphy (Marty, 2001, 2004), the *Faciès Rognacien* is attributed to the Maastrichtian and early Danian.

Previous work has suggested that the K-T boundary has to be placed in the upper part of the Rognacien, and not in the Vitrollien (e.g., Bessière et al., 1980; Galbrun, 1989; Rocchia et al., 1989; Westphal and Durand, 1990; Galbrun et al., 1991; Cojan et al., 1998; Bousquet and Vianey-Liaud, 2001), although no unequivocal evidence has been provided as yet for a golden spike of the K-T boundary.

Within the research area, the *Faciès Rognacien* is composed of a sequence of 15–25 m of palustrine carbonates without intercalated clastic material. The succession can generally be subdivided (from the base to the top) into four units: lower marl, lower limestone, upper marl, and upper limestone (Figs. 3 and 4). These correlate with the M1, C1a/b, M2, and C2 subdivisions of Peybernès and Combes (1999), who identified paleokarstic megafeatures and defined erosional and karstic paleosurfaces (discontinuities) at the base and the top of the limestone units. However, this study does not provide evidence for the existence of such paleokarstic megafeatures.

The transition from the underlying Poudingue Fleuri to the lower marl unit of the *Faciès Rognacien* is not clearly marked. In this work, the limit has been defined where the clastic content falls to zero. The upper boundary is well defined, and the overlying *Faciès Vitrollien* rests directly upon the upper limestone unit (Fig. 3, section 2). The base of the *Faciès Vitrollien* consists of clays with only minor *Microcodium* compared to the rest of this unit, where *Microcodium* is abundant or even rock-forming.

Besides abundant *Microcodium*, the *Faciès Rognacien* is almost barren, even within the marliest layers, many of which could be classified as hydromorphic paleosols of the freshwater marsh facies. This is consistent with the highly bioturbated and oxygenated nature, as well as the pedogenic overprinting, of palustrine carbonates, which are both factors that are unfavorable to fossil preservation. Nevertheless, paleontological and paleoecological data gained from screen-washed samples and the analysis of thin sections proved critical in resolving the complex history of many lithofacies, especially those of the lacustrine pond facies association, where gyrogonites and encrusted stems of charophytes, oncoids, and rare ostracodes are the only recognizable primary lacustrine features. The lower and upper marl units contain a Maastrichtian charophyte flora, whereas the upper limestone unit contains a Paleocene flora, attributing—at least within the research area—the entire *Faciès Vitrollien* to the Paleocene and indicating that no major depositional changes occurred at the K-T boundary (Marty, 2001, 2004) (Fig. 2).

PETROLOGY AND SEDIMENTOLOGY OF THE *FACIÈS ROGNACIEN*

Typical Palustrine Features

Sedimentological Features

At outcrop scale, the four units of the *Faciès Rognacien* are generally easy to distinguish. The lower and upper limestone units are chiefly gray in color and are highly indurated (Fig. 4). A high

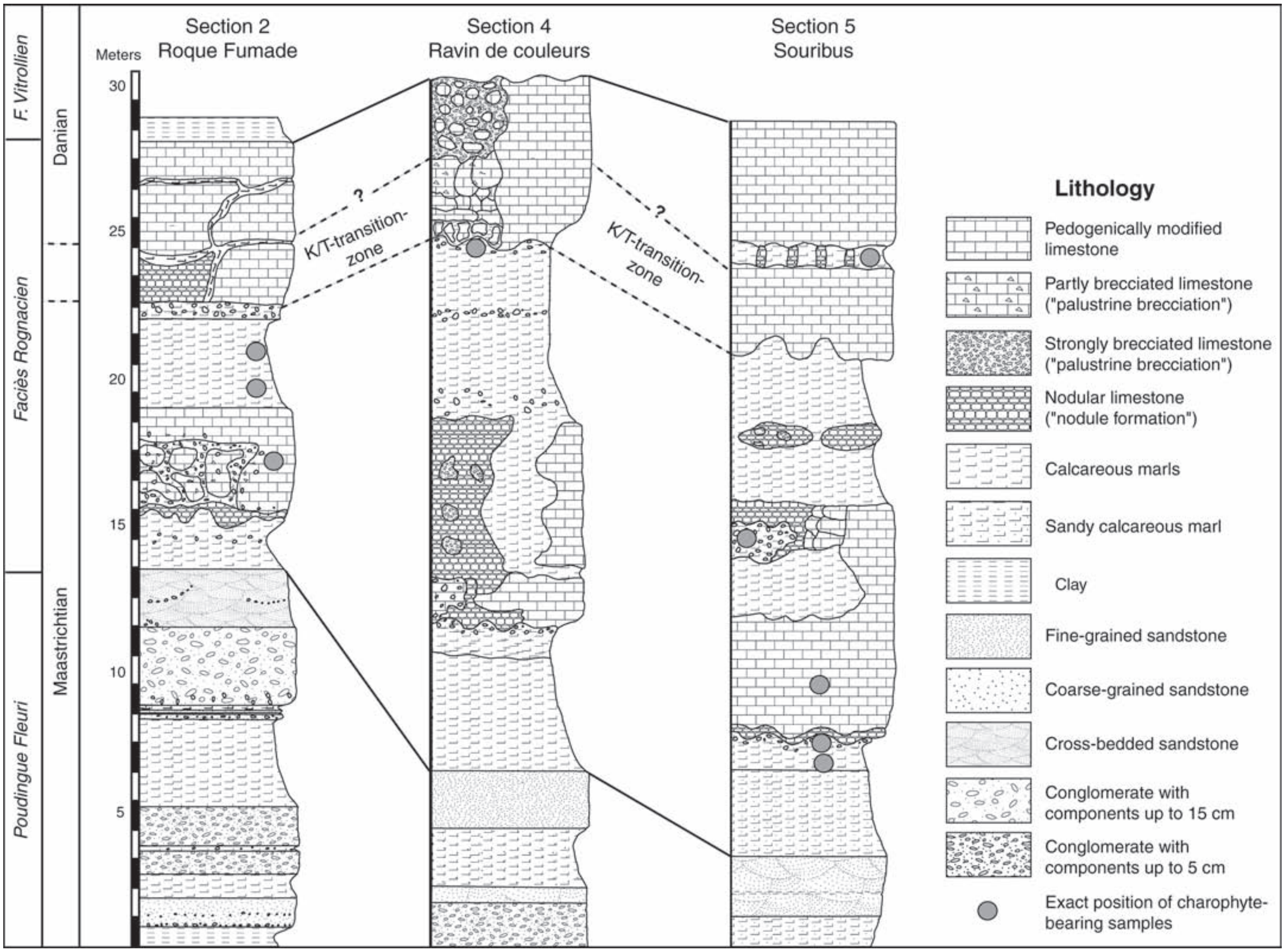


Figure 3. Schematic lithological logs of the sections 2, 4, and 5. Out of 8 sections studied, these are the only sections where charophytes could be isolated out of screen-washed samples, allowing the determination and correlation of the Cretaceous-Tertiary (K-T) transition zone (Marty, 2001, 2004). Throughout the *Faciès Rognacien*, a pronounced lateral variation between and even within the sections in lithology, due to different degrees of macroscopic pedogenic modification (brecciation, nodule formation), is characteristic. Note, however, that this macroscopic lithological appearance of pedogenic modification is not related to the described lithofacies of the freshwater marsh and lacustrine pond facies.

degree of induration—despite limited burial or cementation—is a common feature of palustrine sediments (Alonso-Zarza, 2003) and is explained as the result of mineralogical stabilization and aggrading neomorphism (Wright et al., 1997; Anadón et al., 2000). The gray color indicates zones with reduced iron only, recording rather short subaerial exposure and at least seasonal hydromorphism (Platt and Wright, 1992). The contacts between the marl and limestone units are often very irregular, and doming-upward structures at the top of the limestone units may be observed. Other features of the limestone units include prismatic structures ("columnar limestone"), probably due to root bioturbation (Klappa, 1978a, 1978b; Esteban and Klappa, 1983; Alonso-Zarza et al., 2000), brecciated limestone (Fig. 5A), and nodular limestone (Fig. 5B). The two marl units generally have a gray, beige, or white color, and they appear structureless and homogeneous. However, mottling can locally be pronounced, especially at the base of the *Faciès Rognacien*. Nevertheless, lateral variation in lithology within the *Faciès Rognacien* is typically pronounced. Strongly brecciated limestone may laterally pass into nonbrecciated limestone, and the limestone units may contain intercalated marly layers or marly layers that cut through them (Fig. 3).

Apart from *Microcodium*, the marl units contain very sparse microfauna, and marls bearing charophytes (gyrogonites and encrusted stems) and ostracodes are only rarely found. Throughout the *Faciès Rognacien*, red, yellow, and violet mottling is common, although this may be due to later transformation rather than prolonged exposure and pedogenic reddening ("rubefaction").

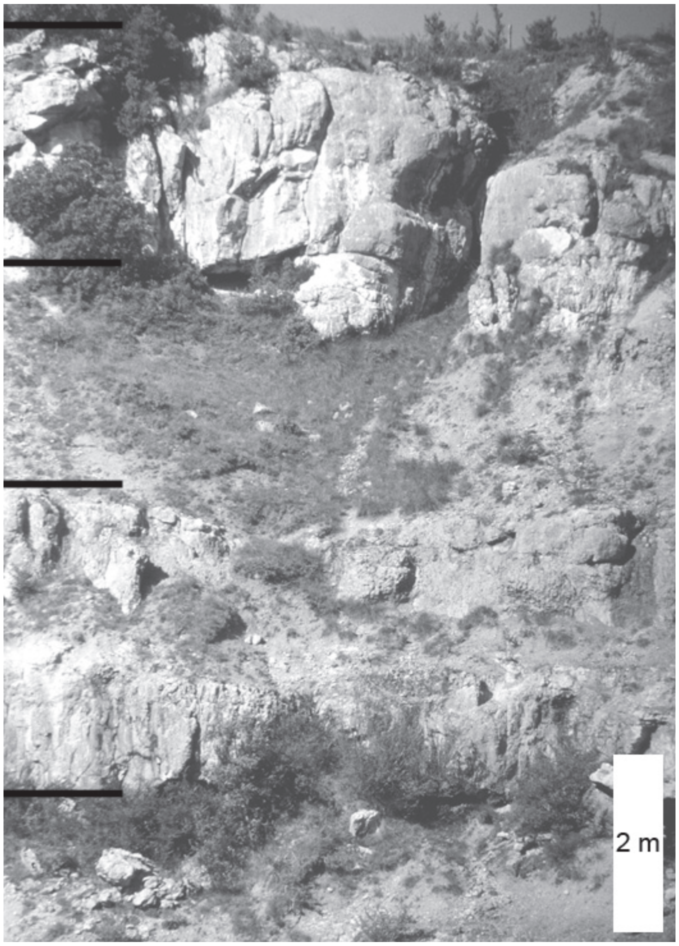


Figure 4. Section 4 (Ravin de Couleurs) showing the typical lithological sequence of the *Faciès Rognacien* within the study area. From base to top, the four units are identified as follows: lower marl, lower limestone (with intercalated marls), upper marl, and upper limestone. In this section, the upper limestone unit is more massive than the lower one.

The *Faciès Rognacien* displays a wide range of palustrine features (alveolar texture, brecciation, coated grains and gravels, cracking, crystallaria, mottling, nodule formation, pseudomicrokarst), which provide evidence of extensive subaerial exposure and pedogenesis. Some of these features may be observed at outcrop scale (Figs. 3 and 5). On a small microscale, several features are commonly intimately associated within the same thin section. Descriptions and interpretations of the most prominent palustrine features of the *Faciès Rognacien* are given in Table 1 and illustrated in Figures 5 and 6.

Further, characteristic features of palustrine carbonates were described in Freytet (1971a, 1971b, 1984), Freytet and Plaziat (1982), Platt and Wright (1992), Alonso-Zarza (2003), and Freytet and Verrecchia (2002). Ginsburg (1975), Hardie (1977), Hardie and Shinn (1986), and Bain and Foos (1993), described the recognition of subaerial exposure surfaces from microfabrics

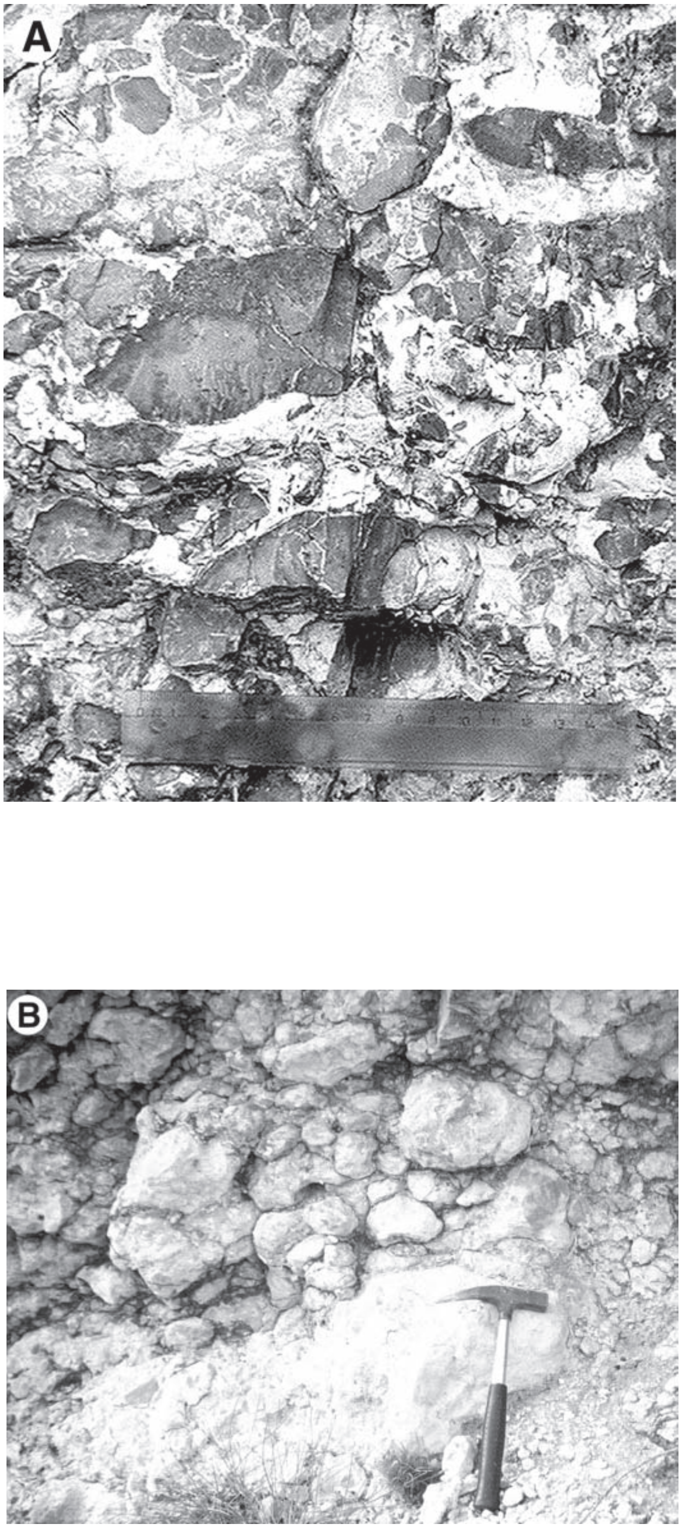


Figure 5. (A) Outcrop photograph showing strongly brecciated limestone, interpreted as monomict and autochthonous desiccation breccia produced by repeated wetting and drying (“palustrine brecciation”). Scale bar is 15 cm. (B) Base of the lower limestone unit of section 1 “L’Encantado”: nodular limestone. Hammer is shown for scale.

TABLE 1. TYPICAL PALUSTRINE FEATURES IDENTIFIED WITHIN THE *FACIÈS ROGNACIEN*

Feature	Appearance in the *Faciès Rognacien*	Interpretation
Alveolar texture Esteban (1974) Figures 6D, 6E	Microscopic: Very common. Occurs as microlaminar micrite or as a network of anastomosing, fine, dark micritic lines or filaments, including irregular, sometimes cylindrical calcite spar-filled voids and vugs, resulting in a highly fenestral fabric. Voids are filled with sparry calcite, similar to crystallaria. The micritic network may exhibit a strong biogenic fabric, which can easily be confused with microbial stromatolites or tufas (Wright et al., 1988).	Steinen (1974) suggested that the fabric may result from the formation of discrete channelways within sediment that has been penetrated by rootlets, and Klappa (1978b) and Esteban and Klappa (1983) described alveolar texture as the product of coalesced mm-sized rhizoliths. Bain and Foos (1993) suggested that alveolar texture resulted from root penetration and diagenetic alteration. Flügel (2004), however, stated that dark cauliflower networks may also have originated from migration of colloidal Fe-solution in argillaceous micrite.
Brecciated limestone (desiccation breccias) Figures 5A and 6B	Microscopic: Intraclasts are irregularly shaped, more or less dark, (sub-) rounded, up to several mm in size, and exhibit sharp to diffuse boundaries. Fissures, cavities, and residual voids are generally filled with sparry calcite cement. Macroscopic: Made up of angular intraclasts with well-defined boundaries, each several mm up to several cm in size. Jigsaw fits between adjacent clasts common.	Angular intraclasts with jigsaw fit indicate in situ genesis without mechanical reworking. During periods of emersion (lowstands), carbonate mud may become partly lithified and wetting-and drying-related shrinkage creates planar voids (desiccation cracks). During flooding, fissures and cavities may be partially filled with fine carbonate material, and pseudomicrokarst structures may form. Typical of palustrine carbonates forming in a semiarid climate (Platt and Wright, 1992). Has also been called "autobrecciation," resulting in "pseudoclast"-containing "pseudobreccias" (Armenteros et al., 1997).
Coated grains and gravels Peryt (1983) Figure 6F	Microscopic: Coated grains include rounded to angular carbonate intraclasts. Coating appears either as micrite envelope or as dark micritic laminae consisting of iron-rich clay material. Micrite envelopes are smooth and regular; iron-rich laminae are generally irregular. Seldom, several generations of coatings may be observed.	Grains and gravels might form through desiccation and mechanical reworking or fenestral fabrics and roots with associated fungi (Alonso-Zarza et al., 1992b) during an early diagenetic process called "grainification" (Mazullo and Birdwell, 1989; Wright, 1990). Micrite coating results from rolling during mechanical reworking, iron-coatings from remobilization of iron-rich clay material that was derived from overlying soils.
Cracking Figures 5A, 6A, 6B, 6C, and 7D	Microscopic: Vertical, horizontal, planar horizontal, oblique, and curved cracks. Circumgranular cracking is prevalent and well developed. Cracks are commonly filled with sparry calcite cement. Macroscopic: Vertical cracks (vertical joint planes sensu Brewer, 1964), horizontal cracks (horizontal joint planes, sheet cracks), planar horizontal cracks, oblique cracks (skew planes), and curved cracks (craze planes).	Commonly associated with roots or induced by desiccation. Circumgranular cracking (and nodule formation) is believed to be the result of repeated wetting (expansion) and drying (shrinkage). Cracking might reflect minor pedogenic modification of the original carbonate texture during lake regression. Subsequent phreatic cementation filled the cracks with sparry cement.
Crystallaria Figure 6E	Microscopic: Consists of a mosaic fabric of microsparitic calcite crystals with a diameter of 5–10 microns. Often, crystallaria occur localized and patchy or in association with alveolar texture.	Crystallaria result from complex and repetitive phases of recrystallization of nodules or mudstones during pedogenic modification, whereas the mosaic fabric clearly indicates crystal growth.
Idiomorphic quartz	Microscopic: Very scarce, never associated with other clastic material. Macroscopic: Frequent, 0.2 mm to several mm in diameter, (bi-) pyramidal. Frequently associated with gyrogonites and *Microcodium*.	Authigenic precipitation of quartz occurs during diagenesis if the sediment contains circulating salinar solutions and if pH conditions are slightly alkalic (Chilingarian and Wolf, 1988). Authigenic quartz is also described from oncoids and stromatolites (Winsborough et al., 1994).
Mottling Figures 6F and 8C	Microscopic: Mottled areas form irregular, dark haloes of varying intensity with diffuse or rarely sharp boundaries. Locally outlined by circumgranular cracks, often associated with nodular limestone fabrics. Macroscopic: Red, yellow to beige and violet colored patches, each a few cm in diameter.	Redistribution of iron and hydroxides in hydromorphic carbonate soils during conditions of fluctuating water table or Eh and Ph, if parental carbonate contains several percent of clay and if its total iron content exceeds 1.5%–2% (Bown and Kraus, 1987; Retallack, 1990). Results in cements which are slightly richer in clay and iron oxide (Valero Garcés et al., 1994).
Nodular limestone Freytet (1973) Figures 5B and 6C	Microscopic: Contains rounded intraclasts up to several mm in size. Intraclasts are similar to the surrounding matrix and are composed primarily of micrite. Macroscopic: Frequent at top or base of limestone units. Size of nodules varies between several cm up to 20–30 cm. If the intercalated marly matrix has already been eroded, the beds exhibit a "pseudo"-conglomeratic aspect.	Mainly due to desiccation and the subsequent formation of planar and curved fissures. Might also be favored through brecciation by recrystallization. In modern soils, nodule formation of carbonate occurs in the zone of an oscillating water table due to repeated flooding (Ruellan, 1967).
Pseudomicrokarst Plaziat and Freytet (1978) Figures 6D and 7D	Microscopic: Irregular, vertically elongated cavities ("fenestrae") commonly filled with complex, polyphased, fine-grained sediment (crystalline, vadose silt) reworked and rounded *Microcodium* debris, and other, larger rounded intraclasts. Some cavities exhibit a lobate shape suggesting that they may have resulted from dissolution or disintegration of *Microcodium* colonies. Residual voids are filled with phreatic sparite cement.	Enlarging of a complex network of root traces and horizontal cracks, with a polyphased filling of coarse and fine internal sediment and varied cements. During dry seasons, the vegetation on carbonate mud (reed or rooted aquatic plants like charophytes) may disappear, leaving root cavities behind. These cavities get enlarged through subsequent water circulation and are filled up before the water level rises again.

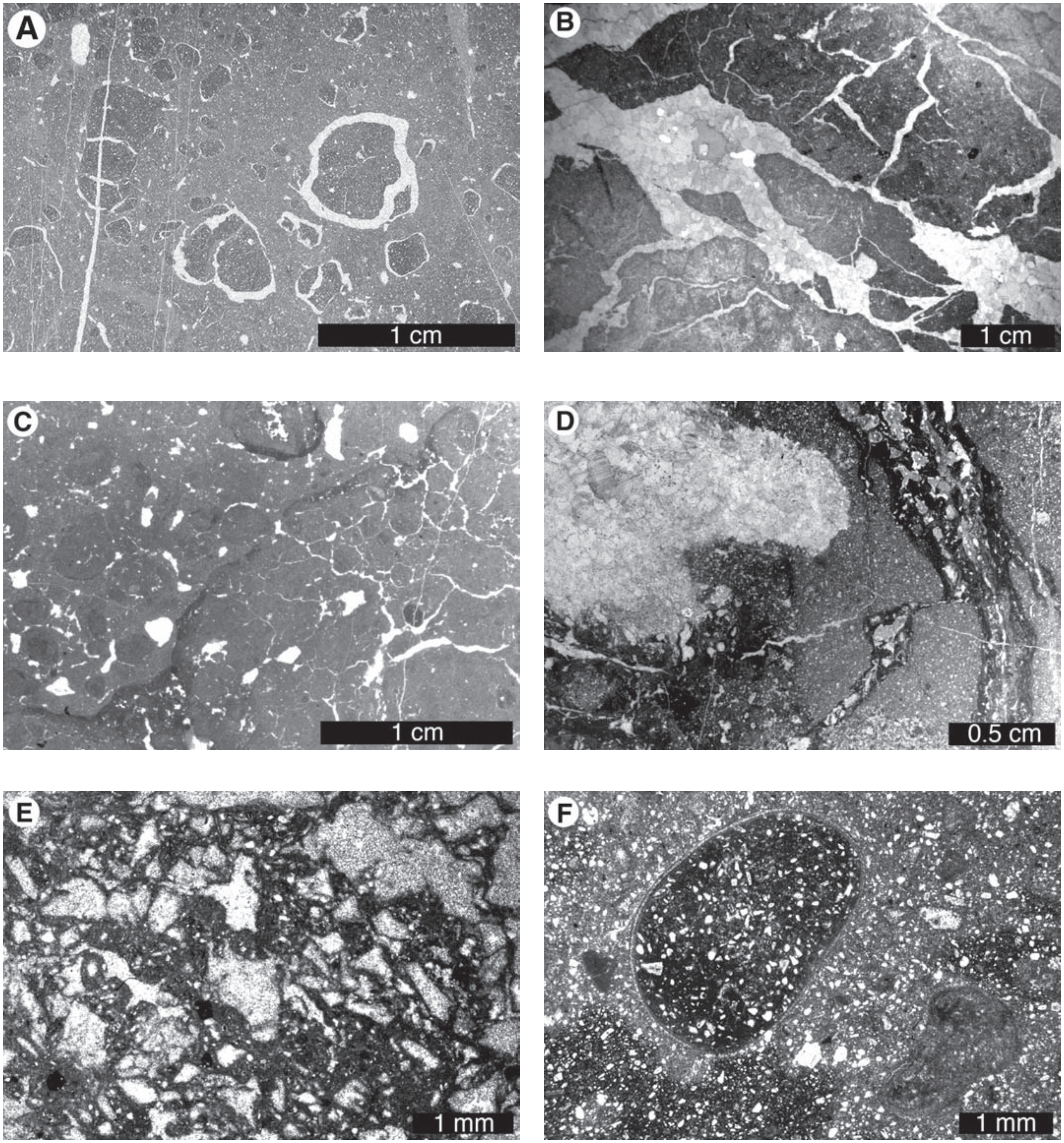


Figure 6. Typical palustrine microfabric features of the *Faciès Rognacien* (for a more detailed description, see also Table 1): (A) Circumgranular cracking (curved planes) in a *Microcodium*-bearing wackestone. Cracks are filled with sparry calcite. (B) Partly brecciated limestone (“palustrine brecciation”). Residual patches of micritic material are intensely fissured, but fit and connection with the adjacent parts clearly indicate that they have not been transported. (C) Nodular limestone, here a mudstone of the freshwater marsh facies association. (D) Rhizolith exhibiting alveolar texture: dark micritic filaments outlining elongate vugs and tubiform pores filled with articulated *Microcodium* colonies (gray, roundish patches) and vadose silt. The pseudomicrokarst cavity (top left) shows a geopetal filling of crystalline (vadose) silt. (E) Alveolar texture: irregular and cylindrical fenestrae and tubiform pores outlined by micritic filaments. The cavities are filled with vadose silt and blocky calcite (crystallaria). (F) Micrite-coated rounded ferruginous intraclast. Intraclast and matrix is composed of *Microcodium*-bearing wackestone to packstone.

in peritidal carbonates, which show many textural similarities with palustrine carbonates.

Paleoecological Features

Microcodium

Complete, articulated colonies of *Microcodium*, as well as reworked, disarticulated colonies, are found in screen-washed samples and in thin sections. *Microcodium* always exhibits the same morphotype (type 1 sensu Bodergat, 1974 and Plaziat, 1984). In thin sections, *Microcodium* shows "corn-cob" colonies in longitudinal (Freytet and Plaziat, 1982; Plaziat, 1984) or spheroidal "rosette" structures in transverse sections (Freytet and Plaziat, 1982; Kosir, 2004) (Fig. 7A). In situ colonies are found in all sorts of cracks and cavities resulting from desiccation and root penetration. Here, they are commonly associated with dissolution and intense corrosion of the adjacent carbonate substrate. However, articulated colonies are also commonly observed within mudstones lacking any other evidence of subaerial exposure. *Microcodium* structures appear to have been very fragile and readily subject to disintegration into single prisms (Fig. 7B). These prisms are a common feature in all reworked, bio- or pedoturbated lithofacies and are thus widespread in their distribution. If the prisms are slightly rounded or corroded, they become harder to identify as *Microcodium* (Figs. 7C and 7D). Also common is the association of reworked *Microcodium* prisms with articulated colonies, indicating repeated periods of *Microcodium* growth and reworking.

The term *Microcodium* was introduced by Glück (1912). *Microcodium* is a problematic calcitic microfeature of many calcretes and paleosols, and there is considerable controversy surrounding its origin and possible relation with calcified plant roots (Esteban, 1974; Freytet and Plaziat, 1982; Freytet, 1984; Jaillard

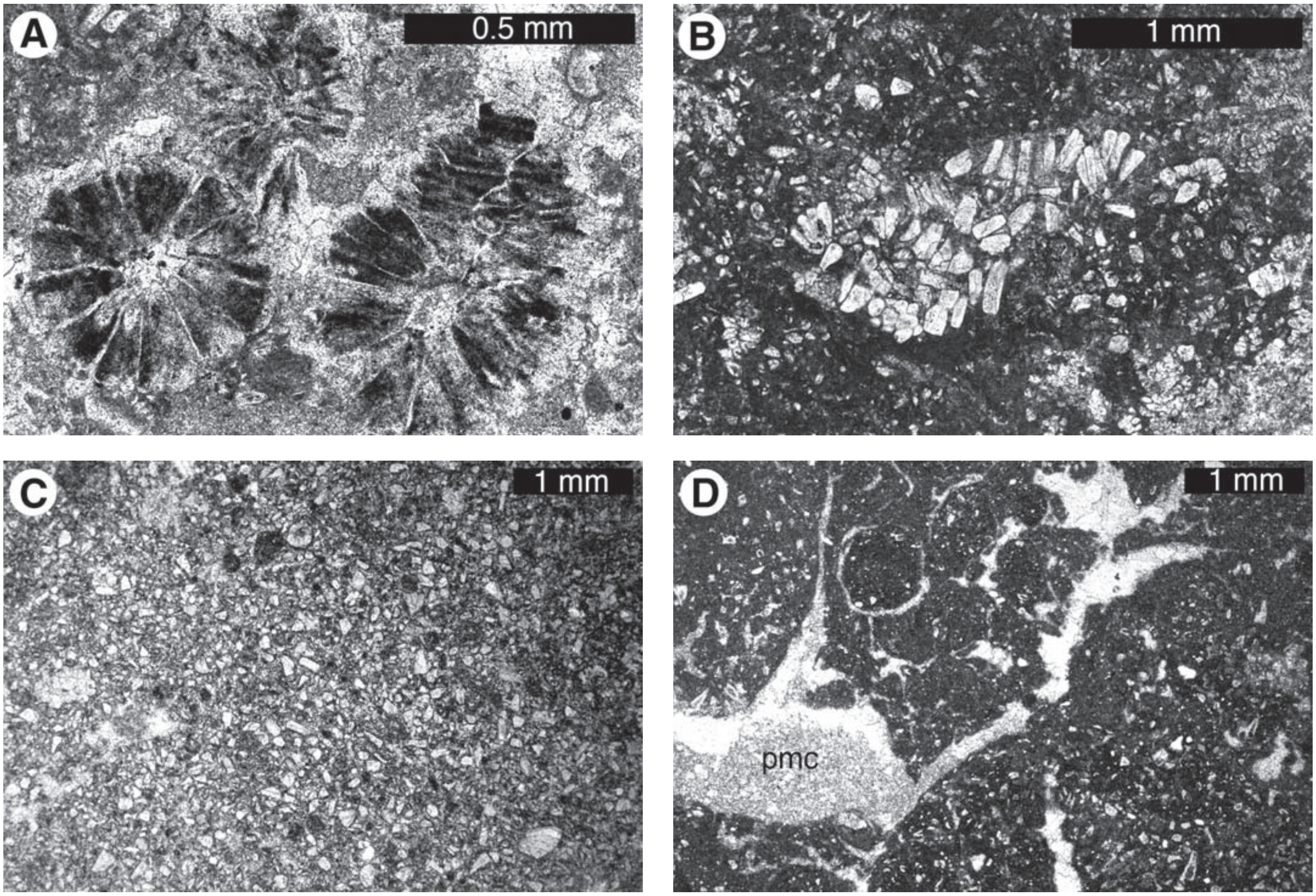


Figure 7. Lithofacies of the freshwater marsh facies association. (A) Mudstone with *Microcodium* colonies ("rosettes") in a micritic matrix. Transverse sections of *Microcodium* colonies show the typical "rosette" structure, associated with corrosion of the matrix at its margins. (B) *Microcodium*-bearing wackestone to packstone with partly disarticulated *Microcodium* colony. Reworked prisms exhibit marginal corrosion and rounding, suggesting multiple phases of growth and reworking. (C) *Microcodium*-bearing packstone containing single prisms and a disarticulated colony (lower right). (D) *Microcodium*-bearing wackestone showing nodule formation associated with circumgranular cracks, mottling, and pseudomicrokarst cavities (pmc), which are filled with crystalline (vadose) silt and blocky calcite.

et al., 1991; Wright et al., 1995; Freytet et al., 1997; Kosir, 2004). However, despite its controversial origin, *Microcodium* is a clear indicator of terrestrial conditions, provides evidence for subaerial exposure, and may be used as a criterion for the recognition of paleosols (Klappa, 1978b; Alonso-Zarza et al., 1998). Recently, Kosir (2004) suggested that its formation takes place during early stages of soil development, probably reflecting nutrient-acquiring mechanisms used by certain types of specific types of vascular plants of a pioneer community that are able to rapidly colonize nutrient-poor carbonate substrates during relatively short-lived phases of subaerial exposure.

Charophytes

Charophyte remains (gyrogonites, encrusted gyrogonites and stems) are common in the *Faciès Rognacien* and are present in both screen-washed samples and thin sections (Fig. 8). Charophyte remains occur in all four units of the *Faciès Rognacien*, but not in all sections studied. However, in sections where charophytes are present, they sometimes occur in several units (e.g., sections 2 and 5 in Fig. 3).

The presence of cortical cells identifies fragments of charophyte stems within oncoid nuclei and other intraclasts (Figs. 8A and 8B). Charophyte stems may serve as nuclei for additional inorganic or organic carbonate precipitation. Inorganic encrustation of stems can be explained by photosynthetic removal of CO_2 and HCO_3^-, leading to the precipitation of calcium carbonate. Some encrusted charophyte stems show laminated stromatolite-like structures formed by epiphytic cyanobacteria, which appear to develop after eutrophication of nutrient-poor environments (Martín-Closas, 1999). The diverse modes and degrees of epiphytic calcification may produce different forms of calcification and fragmentation of the charophyte stems, as illustrated in Freytet and Plaziat (1982) and Schneider et al. (1983).

Modern charophytes live in shallow, littoral zones of temperate to warm, alkaline freshwater lakes, where they are the characteristic floral element. They occur in the photic zone, to a maximum depth of 15–20 m, although the presence of stems usually suggests depths of less than 10 m (Cohen and Thouin, 1987; Garcia, 1994). Charophytes commonly occur together with ostracodes in low-diversity assemblages (Dean and Fouch, 1983). Encrusted stems are delicate structures, and cannot be transported far. Preservation is therefore only possible in a low-energy environment without significant currents or water turbulence (Dean and Fouch, 1983).

FACIES AND FACIES ASSOCIATIONS

The entire *Faciès Rognacien* is essentially made up of two types of carbonate facies associations. These are the (1) freshwater marsh facies, and (2) lacustrine pond facies associations. As all carbonates are pedogenically modified, the lacustrine pond facies is primarily identified on the basis of lacustrine paleoecological evidence such as the occurrence of charophytes and, to a lesser degree, ostracodes. The freshwater marsh facies, on the other hand, includes all pedogenically modified carbonates that do not contain readily identifiable primary lacustrine features. Both facies associations are characterized by the widespread presence of fabrics and textures recording emersion and pedogenesis (Table 1; Fig. 6). Several different lithofacies have been identified in each of the two facies associations, reflecting a complex spectrum of different degrees of emersion, pedogenesis, and associated reworking.

Facies Association 1: Freshwater Marsh Facies Association

Calcareous Marls

Beige to yellow calcareous marls, which have thicknesses up to 3 m and exhibit mottling on a macroscopic scale, make up most of the lower and upper marl unit. Screen-washed samples yielded articulated *Microcodium* colonies and ferruginous nodules, but never remains of a lacustrine fauna or flora.

Interpretation. The presence of abundant, generally articulated *Microcodium* colonies suggests that these marls were formed in the freshwater marsh facies. This is supported by the complete absence of charophytes and other lacustrine remains.

Mudstones

The lower and upper limestone units are primarily composed of fairly massive layers of gray to beige homogeneous micritic limestones that lack any fossil allochems, siliciclastic material such as quartz, lamination, or bedding structure. Typically, the limestones are brecciated (Figs. 5A and 6B) or exhibit nodular fabrics accentuated by circumgranular cracking (Fig. 6C). Rarely, they contain crystallaria and colonies (Fig. 7A) or reworked prisms of *Microcodium*.

Interpretation. The mudstone texture suggests low-energy sedimentation. The general absence of any bedding structure implies bioturbation of the sediments, and the absence of siliciclastic material suggests a closed environment. Palustrine brecciation, nodular fabrics, and circumgranular cracking indicate pedogenic modification. The degree of pedogenic modification may be estimated, where *Microcodium* is present, by the ratio of *Microcodium* colonies to isolated prisms. Within the *Faciès Rognacien*, this is the most abundant and typical lithofacies.

Microcodium-Bearing Wackestone and Packstone

These massive gray limestones are notable in thin section as *Microcodium* wackestones to packstones with strong evidence of pedogenic modification (brecciation, circumgranular cracking, nodular fabric). *Microcodium* is present within and supported by the micritic matrix and is mostly disarticulated (Figs. 7B, 7C, and 7D). Detrital quartz is absent.

Interpretation. The occurrence of different features again suggests a complex history. The carbonate mud was subjected to emersion and pedogenic overprinting, apparently during periods of low water table. *Microcodium* colonies could then have

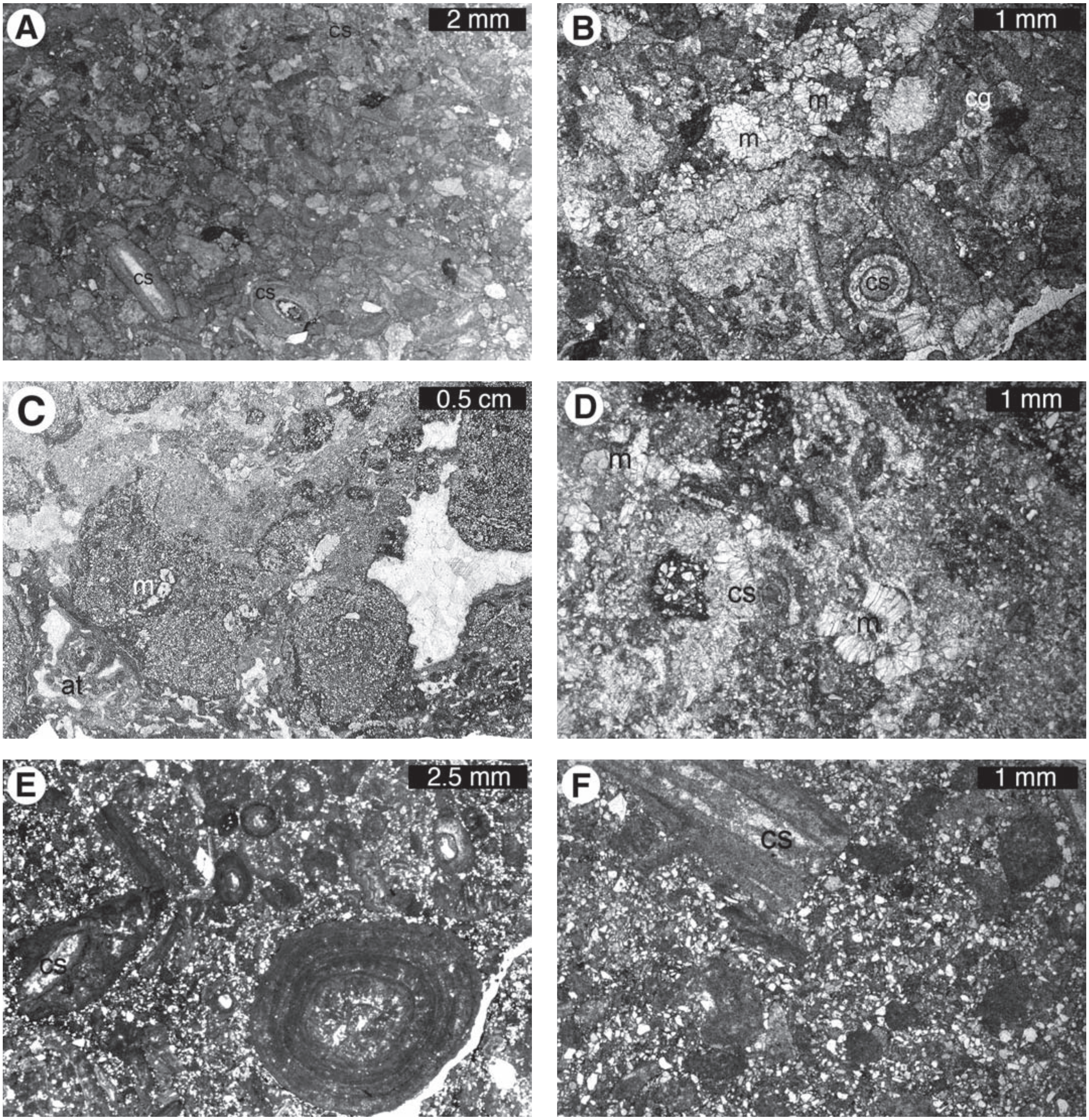


Figure 8. Lithofacies of the lacustrine pond facies association. (A) Intraclastic packstone (granular limestone). Subrounded to angular intraclasts include encrusted charophyte stems (cs), a few poorly developed oncoids, *Microcodium* prisms, and colonies. Some grains exhibit ferruginous coatings. (B) Detail of A, showing encrusted charophyte stem (cs), gyrogonite (cg), and laminar *Microcodium* colonies in longitudinal section (m). (C) Intraclastic nodule wackestone or packstone with ferruginous intraclasts, alveolar texture (at), *Microcodium* colonies (m), and spar-filled vugs. Individual intraclasts are distinguished from the matrix by abundance and state of preservation of *Microcodium* debris and aggregates, and by delineation of ferruginous coatings. (D) Detail of C. The matrix (wackestone) between the intraclasts contains less *Microcodium*-debris and charophyte stems (cs), but clearly more articulated *Microcodium* colonies (m) than the ferruginous intraclasts. Note dissolution associated with *Microcodium* colonies within the matrix and inhomogeneous mottling. (E) Intraclastic rudstone: intraclasts comprise oncoids (alternating layers of thin and thicker micritic laminae around a poorly defined nucleus), encrusted charophyte stems (cs), and other carbonate gravels. The matrix contains abundant reworked and corroded *Microcodium* debris (white clasts). Note the pronounced mottling and ferruginous coatings. (F) Intraclastic floatstone: angular intraclasts include encrusted charophyte stems (cs) and other carbonate gravels. The matrix is a *Microcodium*-bearing (white clasts) wackestone to packstone.

formed in desiccation cracks and around rootlets penetrating into the cracks. Through subsequent water circulation following heavy rains, or in times of raised water level, *Microcodium* colonies were disintegrated and reworked, leading to the redeposition of single prisms. The presence of abundant *Microcodium* "micro-bioclasts," in the absence of other detrital grains of similar size suggests the reworking of *Microcodium* which were proliferating in a freshwater marsh environment. Such environments would have been protected from terrigenous influx by a filter of dense reed or other swamp vegetation (Freytet and Plaziat, 1982).

Facies Association 2: Lacustrine Pond Facies Association

Chalky Marls

These marls are white, chalky, calcareous marls, which are mostly intercalated with nodular limestone (see below) (Fig. 5B), whereas the bed thickness varies laterally between several centimeters up to several tens of centimeters. Screen-washed samples yielded abundant gyrogonites and encrusted stems of charophytes, partially articulated to articulated *Microcodium* colonies, and authigenic idiomorphic quartz.

Interpretation. The presence of charophyte remains implies a primary lacustrine origin. *Microcodium* indicates later pedogenic overprinting during lowstand of the water table in a vadose environment. Furthermore, articulated *Microcodium* colonies suggest minor reworking. The white color, the chalky nature, and the absence of mottling suggest at least seasonal hydromorphism.

Intraclastic Packstones (Granular Limestones)

This facies is composed of nodular limestones that contain carbonate nodules up to a diameter of ~20 cm, often intercalated with white calcareous marls (see above) (Fig. 5B), or massive gray limestones. Polished sections show that the carbonate nodules consist of angular (0.5–1 cm) intraclasts as well as of (sub-) rounded (0.2–0.5 mm) calcareous "gravels" (Figs. 8A and 8B). Many of the clasts are made up of encrusted gyrogonites and charophyte stems. The charophyte gyrogonites and stems exhibit diverse degrees of fragmentation, but are generally well preserved and not deformed. The clasts are locally outlined with circumgranular cracks or ferruginous coatings. The matrix is micritic, although large spar-filled vugs and recrystallized areas are common. Ostracodes and molluscan shell fragments are sometimes present.

Interpretation. Charophytes and other macrophytes were apparently encrusted due to preferential Ca-precipitation onto a biological substrate as a result of CO_2 drawdown through photosynthetic activity. Subsequent degradation of the encrusted macrophytes provided a range of intraclastic material. The low degree of deformation and fragmentation of charophyte gyrogonites and stems indicate that compaction and crushing was negligible or that it predated encrustation. This also points to a low-energy environment, probably within charophyte meadows, which are commonly developed within carbonate lakes at shallow depths of less than 10 m (Murphy and Wilkinson, 1980; Cohen and Thouin, 1987; Garcia, 1994). During a phase of low water table, the "primary" lacustrine sediment was subjected to emersion, resulting in minor pedogenic modification (limited desiccation and root brecciation). A rather short time of subaerial exposure is also indicated by the general lack of *Microcodium.*

Intraclastic (Nodule) Wackestone and Packstone

This facies is composed of breccias containing (sub-) rounded ferruginous intraclasts with diameters of several millimeters to centimeters (Fig. 8C). The intraclasts are made up of *Microcodium* wackestones to packstones, including reworked *Microcodium* debris and rarely articulated colonies floating in a dark ferruginous, argillaceous micritic matrix (Fig. 8D). The intraclasts also contain rare charophyte gyrogonites and stems. The matrix between the intraclasts is micritic and contains *Microcodium* debris as well as abundant articulated colonies (Fig. 8D), alveolar texture, and up to 1 cm big vugs, filled with blocky calcite cement.

Interpretation. This complex lithofacies can only be explained by several subsequent events of emersion, involving pervasive microkarstic and desiccation brecciation of the above described chalky marls and intraclastic packstones, followed by reworking back into the "lacustrine pond" setting. Thus, different scenarios may lead to this lithofacies. One possible means of formation might be that *Microcodium* formed around ponds during periods of low water table. A rise in water level reworked the colonies, and single prisms settled down, with charophytes growing during the subsequent period of high water level. During a second phase of emersion, the charophyte- and *Microcodium*-bearing sediment was partially indurated, and intraclasts formed through palustrine brecciation or nodule formation. At the same time, new *Microcodium* colonies were established. During the subsequent period of high water table or as a result of heavy rainfall, these intraclasts were reworked, slightly rounded, and redeposited within another *Microcodium*-bearing mud. During a further period of emersion, another generation of *Microcodium* colonies and alveolar texture formed to give this lithofacies its final, complex appearance. The different size and form of intraclasts indicates reworking during short periods of high-energy events and suggests that they have not been transported far.

Intraclastic Floatstone and Rudstone

This lithofacies occurs seldom and only at the base of the *Faciès Rognacien*. It is composed of up to 30 cm of sandy, marly limestones that exhibit a very pronounced lateral change in the content and size of intraclasts. Thin sections reveal that intraclasts include encrusted charophyte stems and gyrogonites, structureless carbonate intraclasts, and, locally, oncoids (Figs. 8E and 8F). The size of encrusted charophyte stems is up to 1–2 cm in length, while the gyrogonite-bearing intraclasts are mostly only a few millimeters across. The carbonate intraclasts are generally on the order of a few millimeters in size, although some may reach up to one centimeter in diameter. Oncoids have a spherical to elongate form and a diameter of several millimeters up to 10 cm. They constitute alternating fine-grained more or less dark micritic layers with wavy and cauliflower-like fabrics. Nuclei are poorly defined, but where present, they comprise small lithoclasts, or, more rarely, charophyte stems (Fig. 8E). These rocks have a matrix to grain-supported fabric with a wackestone-packstone matrix containing reworked and strongly corroded *Microcodium* prisms.

Interpretation. As with the intraclastic packstones, intraclastic floatstones and rudstones are the result of brecciation due to emersion, reworking and resedimentation of lithified carbonate grains and gravels. They are a common facies in the littoral realm of modern lakes (Murphy and Wilkinson, 1980; Platt and Wright, 1991). Oncoids commonly grow in alkaline, Ca-rich waters in river channels, marshes, lakes, and floodplains (Monty, 1981). Recent freshwater oncoids generally grow in rather quiet shallow-water environments (benches or flats of lakes) with temporary turbulence during floods (Monty, 1972). Pronounced changes in clast size and the lateral strong variation from matrix- to grain-supported fabrics suggest transport over short distances only. This indicates deposition in a pond that was repeatedly subjected to emersion, resulting in the formation of abundant *Microcodium* colonies and carbonate intraclasts, which were in turn reworked during the next rise of the water level or by water movement (waves) due to storms.

DISCUSSION

The palustrine environments of the *Faciès Rognacien* developed within a continental succession in a tectonically bounded foreland basin. The palustrine carbonates are intercalated with floodplain deposits within a fluvial-lacustrine system. This palustrine environment is likely to have passed into a more lacustrine environment eastward along the river Aude (Peybernès and Combes, 1999), fluvial-alluvial environments to the south, and marine environments progressively toward the west. Alonso-Zarza (2003) suggested that palustrine deposits mostly form during periods of strongly reduced subsidence with the limited accommodation space of overfilled basins, leading to the deposition of palustrine facies as highstand depositional systems. Also Platt and Wright (1992) stated that palustrine deposits are common in relatively stable basins, typically forming during periods of tectonic quiescence when clastic supply from inflowing alluvial-fluvial systems is reduced. Platt and Pujalte (1994) and Platt (1995) noted that the formation of palustrine carbonates in the Cretaceous of Spain was associated with the subaerial exposure and peneplanation of an underlying carapace or pediment of marine Jurassic carbonates where clastic supply was limited. A similar subcrop configuration might also be suggested for the *Faciès Rognacien*.

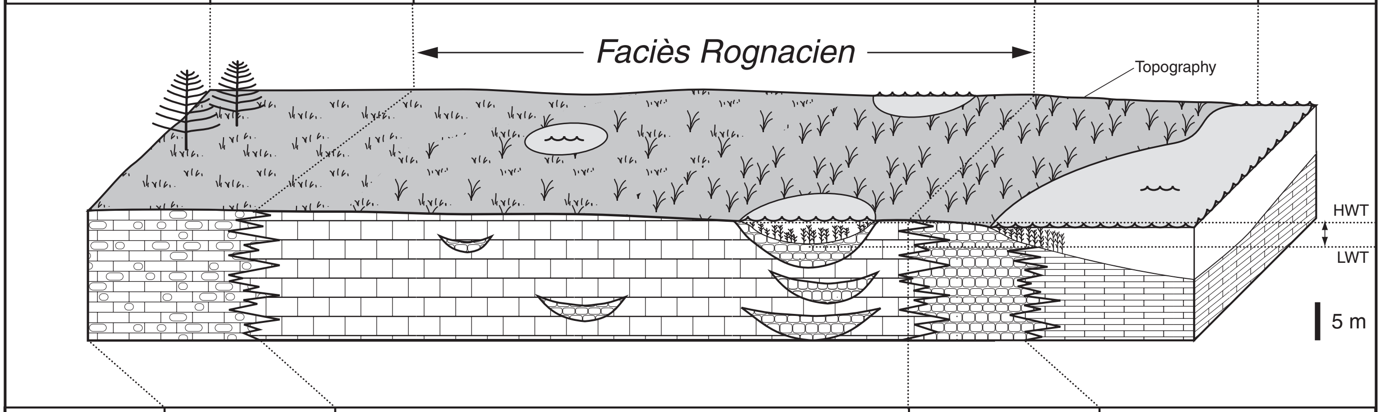
Paleoclimate

Climate is a critical control factor in the development of lacustrine and palustrine successions (Platt, 1989b, 1989c; Platt and Wright, 1992; Camoin et al., 1997). Climate not only controls the lacustrine and palustrine environment, but also the surrounding, usually siliciclastic, depositional environments. The development of palustrine carbonates is favored in climates with seasonal aridity and environments of low clastic detrital supply or carbonate-dominated source terrains (Alonso-Zarza et al., 1992a; Alonso-Zarza, 2003). Nevertheless, Schullenberger et al. (2004) stated that the presence of a groundwater-fed regional water table is more important than climate in the formation of extensive palustrine deposits. Further, Dunagan and Turner (2004) noted that primary groundwater discharge may give the appearance of increased humidity in an otherwise semiarid climate.

However, according to Platt and Wright (1992), palustrine sequences may form under three different types of climate: semiarid, intermediate, and subhumid. These three climate regimes are tied to specific palustrine features, documented from Carboniferous to Quaternary palustrine sequences (Platt and Wright, 1992; Dunagan and Driese, 1999). Platt and Wright (1992) further developed a freshwater exposure index, similar to the marine exposure index of Ginsburg et al. (1977); it links characteristic palustrine features to both hydroperiod and seasonality. The hydroperiod is defined as the mean number of days per year during which the ground surface at a given site is covered with water (Ginsburg et al., 1977; Platt and Wright, 1992).

Throughout the *Faciès Rognacien*, neither evaporites and calcretes (typical for a semiarid setting) nor blackened pebbles, coal, and lignite horizons (typical for a subhumid setting) have been found. However, *Microcodium* (typical for an intermediate setting) is abundant, and evidence of desiccation (brecciation and nodule formation, pseudomicrokarst) is relatively common. Thus, the *Faciès Rognacien* may be placed between the subarid and intermediate types of Platt and Wright (1992). Assuming that the exposure index model of Platt and Wright (1992) is applicable to the palustrine carbonates of the *Faciès Rognacien*, these carbonates may have an estimated hydroperiod somewhere in between 100–320 d (Fig. 9), indicating that pond development and lake expansion was probably associated with a distinct wet season. Those sections in the *Faciès Rognacien* displaying stronger evidence of subaerial exposure may record deposition on paleotopographic highs or distal areas (“prairies”), where flooding was rare and pedogenic modification was prolonged. The fact that all carbonates of the lacustrine pond facies are pedogenically modified, at least to some extent, also suggests that the ponds dried out during the dry season. The presence of Fe-coatings, Fe-concretions, and mottling points to a mean annual temperature over 20 °C (Pédro, 1968). Clay mineralogy analyses also support deposition in a warm and seasonally humid climate (Groebke, 2001). In summary, an intermediate, seasonally humid, subtropic climate might be suggested.

Facies	**Palustrine**			**Lacustrine**
Environment	Prairie Ephemeral wetland	Freshwater marsh Perennial wetland	Marginal lake Fringing wetland + littoral	Permanent Lake



Hydroperiod	30-90 days	100-250 days	100-320 days	100-320 days	All year
Exposure Ind.	70-90%	30-70%	10-70%	10-70%	0%
Typical features	Calcretes, black pebbles, root traces	*Freshwater marsh:* pseudo-microkarst, pronounced pedogenic modification, articulated *Microcodium* colonies *Ponds:* little pedogenic modification, isolated occurrence, charophyte stems + gyrogonites, ostracodes, *Microcodium* debris		Erosional breccias, oncoids, charophytes, ostracodes, pedogenic features	Lamination, no pedogenic modification, charophyte gyrogonites, fish
Facies associations in the Faciès Rognacien		Freshwater marsh facies association (Carbonate freshwater marshes)	Lacustrine pond facies association (Ephemeral, shallow, small ponds)		
Lithofacies of the Faciès Rognacien		Calcareous marls Mudstones *Microcodium*-bearing wacke/ packstones	Chalky marls Intraclastic pack/grainstones Intraclastic wacke/packstones Intraclastic float/rudstones		

HWT	Highest water table
LWT	Lowest water table
	Wooded vegetation
	Swamp vegetation (horsetail, reed)
	Marsh vegetation (sedge, grass)
	Water plant vegetation (charophytes)

Figure 9. Simplified block diagram showing a facies model for a palustrine-lacustrine setting. The freshwater marsh and the lacustrine pond facies associations of the *Faciès Rognacien* are inferred to have been deposited in a freshwater marsh within a wetland environment, where densely vegetated carbonate marshes and swamps prevented siliciclastic input. Extensive charophyte meadows developed in small, shallow, and ephemeral ponds. Open lacustrine facies are not developed, and lateral changes in paleotopography are on the order of a few meters only. The table links paleoenvironment, typical sedimentological and paleoecological features, as well as the described facies associations with the freshwater exposure index of Platt and Wright (1992). The hydroperiod represents the number of inundation days over the year. An exposure index of 100% is equivalent to a hydroperiod of zero days per year.

Paleoenvironment

The carbonates of the *Faciès Rognacien* display indicators both of emergence and of water-saturation (hydromorphism), but clearly do not show any evidence of marine influence. Further, they do not include any deeper-water lacustrine facies (such as laminites), or distal alluvial sediments. Macro- and microfacies analysis allowed the grouping of the various lithofacies into two distinct facies associations, namely the ubiquitous freshwater marsh facies and the relatively much rarer lacustrine pond facies.

Carbonate sedimentation of the lacustrine pond facies took place in shallow and ephemeral ponds, and all lithofacies show some evidence of subaerial exposure and pedogenic modification. These ephemeral ponds may have been connected by groundwater only, a possibility which is also consistent with the absence of any significant clastic input (Alonso-Zarza and Calvo, 2000). The low-diversity invertebrate fauna assemblage and the absence of any vertebrate remains (e.g., fish) suggest elevated environmental stress (alkalinity, oligotrophy, water-level instability) or poor faunal preservation potential (diagenetic conditions preventing preservation); this is consistent with the development of individually isolated, small, very shallow, and probably short-lived ponds at paleolows.

The general absence of shell lags, the rarity of oncoid-bearing facies, and the predominance of mudstone to wackestone textures indicate that wave energies were generally low due to the very small size of the ponds, but, in part, perhaps also because of the baffling effect of extensive stands of aquatic vegetation like charophyte meadows. Nevertheless, high-energy storm events (sheetfloods) occurring sporadically in this generally low-energy system might have been responsible for the formation of intraclastic packstones in the lacustrine pond facies and *Microcodium* wackestones to packstones in the freshwater marsh facies, respectively.

The lack of evaporites points to low salinity. This is supported by the presence of charophytes, which are typical for environments with low salinities of less than 16‰–20‰ (Schudack, 1993; Schudack et al., 1998), even if, for example, Burne et al. (1980) and Mojon (1990) give examples of more saline charophytes. The source of the fine-grained carbonate (typically low-Mg calcite) in palustrine carbonates is poorly understood, but may be polygenetic in origin, reflecting biogenic production from charophytes, ostracodes, molluscs, and cyanobacteria, as well as inorganic and biogenically induced precipitation (Dean, 1981; Platt and Wright, 1992; Alonso-Zarza and Calvo, 2000; Anadón et al., 2000).

The carbonates of the freshwater marsh facies were probably produced biogenically from microbial (blue-green algal) mats (Monty, 1972; Monty and Hardie, 1976), from inorganic or biogenically induced precipitation around charophytes and other vegetation, as well as *Microcodium*. The presence of a fringing vegetation zone of shallow-water marsh and land plants would have acted as an effective barrier to terrigenous clastic input. Tandon and Andrews (2001) suggested that semiarid carbonate flats typically have a low biomass, and under prolonged exposure, the dominantly herbaceous vegetation would leave little or no evidence of the larger root systems as expected from arboreal plants. This could explain why well-developed rhizolites, as well as organic matter, have not been observed in the *Faciès Rognacien*.

The predominance of the freshwater marsh facies and the scarcity of the lacustrine pond facies cannot easily be explained with the "marginal lake facies" model of Freytet and Plaziat (1982) or the marginal lacustrine facies of Platt and Wright (1991). It is suggested that the *Faciès Rognacien* in the study area was deposited in an ancient wetland dominated by carbonate-producing freshwater marshes with some intervening small and shallow ephemeral ponds. Seasonal variations in water table and minor topographic variations across the depositional area could easily explain the distribution and sequence of the various facies. Nevertheless, the depositional environment of the *Faciès Rognacien* as described here might have been located within a wider lacustrine environment, since Peybernès and Combes (1999) noted that the *Faciès Rognacien* becomes more lacustrine eastward along the river Aude. Further, this wetland-lacustrine environment is likely to have passed into fluvial-alluvial environments to the south and marine environments progressively toward the west (Plaziat, 1981).

Modern Analogues

Platt and Wright (1992) stated that difficulties in identifying a convincing modern analogue for palustrine carbonate deposition had hindered the development of facies models for palustrine carbonates. These authors went on to propose the Florida Everglades wetland as an analogue for many aspects of palustrine carbonate deposition. The Everglades, however, are not a lake, nor a lake margin, but a vast, densely vegetated, carbonate freshwater marsh complex, where lakes and ponds make up only a small proportion of the total area (Mitsch and Gosselink, 1993). A fall in water level of only a few meters can cause exposure of wide areas, whereas comparable rises in lake level are unlikely to permit development of a stratified water column (Platt and Wright, 1992).

Today, wetlands are amongst the most important and sensitive ecosystems and cover 6% of the world's surface. They are areas that are periodically flooded, and they are found in every climatic zone and on every continent except Antarctica (Mitsch and Gosselink, 1993). As modern wetlands are very diverse, their definition and classification is extremely problematical (Finlayson and van der Valk, 1995a, 1995b; Scott and Jones, 1995). Among the most widely accepted definitions for a palustrine wetland is the one of Cowardin et al. (1979) (see also Cowardin and Golet, 1995, for recent advances), which was adapted by the U.S. Fish and Wildlife Service. This definition requires "an area of less than 8 ha, a lack of wave-formed or bedrock shoreline features, water depth in the deepest part of the basin of less than 2 m at low water, and salinity stemming from ocean-derived salts of less than 0.5 ppt" (Cowardin et al., 1979, p. 10).

However, despite their abundance, many wetlands are limited in areal extent and form small features relative to their sedimentary basins (Quade et al., 1995). As such, their preservational potential may be limited. Indeed, Deocampo (2002) suggested that wetlands are likely to be difficult to recognize in the sedimentary record, and Liutkus and Ashley (2003) noticed that, as yet, no sedimentological facies models have been developed for (siliciclastic) freshwater wetlands.

To date, the Everglades wetland has been considered by Armenteros and Daley (1998) as a modern analogue for the palustrine Bembridge Limestone (Eocene, Isle of Wight), and by Valero Garcés et al. (1994) for parts of the Upper Freeport Formation (Pennsylvanian, Appalachian Basin). Platt and Pujalte (1994) proposed that an ancient analogue for the Early Cretaceous palustrine system of northern Spain might be represented by the extensive areas of shallow freshwater marshes found in southeastern Iraq around Basra. These environments pass laterally seaward into the marginal marine and peritidal facies of the Persian Gulf (Baltzer and Purser, 1990) and laterally landward into the fluvial and semidesert environments of central Iraq. Valero Garcés et al. (1994) also proposed that the semiarid to subarid carbonate-dominated, extensive wetland of Bahia in northeastern Brazil (Branner, 1910) might form a good recent analogue. Another modern analogue might be provided by Lake Balaton in Hungary (Müller and Wagner, 1978). Recently, Dunagan and Turner (2004) reinterpreted lacustrine sediments of the Late Jurassic Morrison Formation as deposits of groundwater-fed, perennial carbonate wetlands, similar to the Quaternary wetland deposits of the U.S. southern Great Basin (Quade et al., 1995, 2003).

All of the modern analogues listed display a complete spectrum of lake, pond, and soil environments similar to those recorded within the *Faciès Rognacien*. It is thus suggested that the *Faciès Rognacien* was deposited in a seasonal, groundwater-fed, nontidal, carbonate-producing, palustrine (sensu Cowardin et al., 1979) wetland, which was probably characterized by hydrologically closed, ephemeral ponds surrounded by vast, more or less densely vegetated (cf. Hofmann and Zetter, 2005) carbonate freshwater marshes and swamps (Fig. 9). This environment could also have formed within the marginal area of a larger perennial lake complex, or within an extensive fluvial-alluvial plain. The development of these palustrine environments within a lacustrine-fluvial system across a tectonically active foreland basin margin to the north of the Pyrenean foredeep is closely equivalent to the modern setting of the present-day Iraq analogue.

CONCLUDING REMARKS

1. The *Faciès Rognacien* is a very good example for palustrine facies. It exhibits a wide range of classical palustrine features including well-developed palustrine brecciation, nodule formation, horizontal, planar, and circumgranular cracking, pseudomicrokarst, alveolar texture, and *Microcodium*. The abundance and distribution of these features place the *Faciès Rognacien* somewhere between the subarid and the intermediate palustrine climate type of Platt and Wright (1992), an intermediate subtropical climate with an estimated hydroperiod between 100 and 320 d.
2. The palustrine carbonates of the *Faciès Rognacien* show a range of highly varied fabrics and lithofacies that reflect primary depositional setting and subsequent subaerial exposure, brecciation, pedoturbation, and pedogenesis. The various lithofacies recognized have been grouped into two facies associations, the lacustrine pond facies and the freshwater marsh facies, which allow a reconstruction of the paleoenvironment in greater detail.
3. Fossils are extremely scarce throughout the whole *Faciès Rognacien*, particularly in the freshwater marsh facies, where only *Microcodium* is frequently found. Nevertheless, paleontological and paleoecological data gained from screen-washed samples and the analysis of thin sections proved critical in resolving the complex history of many lithofacies, especially those of the lacustrine pond facies, where gyrogonites and encrusted stems of charophytes, oncoids, and seldom ostracodes are the only recognizable primary lacustrine features.
4. Within the research area, the pedogenically modified mudstones of the freshwater marsh facies association are by far the most prevalent. Hence, the *Faciès Rognacien* is predominantly composed of the freshwater marsh facies, where most of the carbonates formed. Only a minor part of the depositional area—probably representing paleolows—can be attributed to the lacustrine pond facies. Thus, the *Faciès Rognacien* may be better characterized as an assemblage of freshwater marsh facies laid down within a carbonate wetland setting (Wright and Platt 1995) rather than pedogenically modified carbonates of a marginal lake setting.
5. The facies associations observed are consistent with deposition within a seasonal, possibly groundwater-fed, palustrine (sensu Cowardin et al., 1979) wetland system characterized by possibly hydrologically closed, ephemeral ponds surrounded by vast, more or less densely vegetated areas of carbonate-producing freshwater marshes. This wetland environment is likely to have passed into fluvial-alluvial environments to the south and marine environments progressively toward the west.
6. Further detailed sedimentological studies and facies analysis of palustrine sequences are essential in any attempts to develop more precise facies models and to compare ancient successions with their still poorly studied modern analogue environments, which occur in a range of carbonate-producing wetlands distributed worldwide.

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