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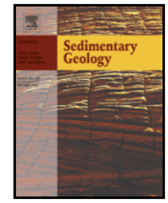

A carbonate palustrine system with marshes and shallow ephemeral lakes (Campanian, northeastern Iberian Basin)

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ABSTRACT

The sedimentary and stratigraphic features of the low-gradient slope carbonate palustrine system of the Fortanete Formation (northeast Spain) during the early Campanian have been studied. The succession of the Fortanete Fm provides depositional record of a progressive transition to continental settings in an area that was predominantly marine for most of the Late Cretaceous. Palustrine systems can be developed in a wide variety of environments, however, modern analogues are scarce. The Fortanete Fm thus presents a great opportunity to study the stratigraphy, the sedimentary features and isotopic composition of a palustrine–marine influenced system. A total of 10 stratigraphic sections distributed along a 40 km wide and 80 km long area have been carried out in order to decipher the facies distribution in the system. This study led to the differentiation of three palaeoenvironments based on predominant lithofacies and sedimentary structures: (1) marshes and shallow low-gradient slope lakes; (2) ephemeral lakes, lake margins and prairies with variable water level and marine influence; and (3) mudflats with evaporites and fine siliciclastic input. The Fortanete Fm serves as an excellent case study for palustrine environments with the presence of typical palustrine features such as pseudomicrokarst, brecciation, black pebbles, desiccation cracks, nodules, *Microcodium*, and fenestral fabric. Most palustrine systems are associated with continental freshwater settings, whereas the Fortanete Fm displays evidence of intermittent marine influence in the distal studied sections. Carbon and oxygen isotope composition is within the range of typical freshwater lake carbonates and also corresponds to isotope composition of palustrine carbonates with marine influence. The Fortanete Fm shares a number of characteristics with freshwater continental and freshwater modern analogues. Comparison with these systems provides new insights on how modern analogues can be used to decipher the complexity of the processes developing these systems in the past.

1. Introduction

Palustrine carbonates are formed under special hydrological conditions and were particularly widespread during Mesozoic and Cenozoic, however, the lack of precise modern analogues makes it difficult to unravel the processes controlling these environments (Platt and Wright, 1992; Alonso-Zarza, 2003; Alonso-Zarza and Wright, 2010). One of the main problems in searching for proper modern analogues and comparing them with the geological record is that palustrine carbonates can be formed in a significant variety of environments: from coastal areas of low relief carbonate platforms (e.g., Martín-Chivelet and Giménez, 1992) to discrete carbonate units within siliciclastic fluvial settings (e.g., Platt, 1989). Many of palustrine carbonates in the geological record have been interpreted as deposits of wetland fringes of shallow, hard-water perennial lakes, following the classic model of Freytet and Plaziat (1982). The Florida Everglades and, recently, the Sian Ka'an Wetlands from the Yucatán Peninsula have been proposed as modern analogues of ancient palustrine deposits corresponding to coastal depositional settings (Platt and Wright, 1992; Platt and Wright, 2023). These models emphasise the dynamic relationships between marginal marine and freshwater carbonate systems described in the framework of progressive transgression of Caribbean carbonate platforms during the late Quaternary and discuss particularly those ancient examples of palustrine deposits which are associated with shallow marine depositional systems (Platt and Wright, 2023).

The Iberian Basin, a large sedimentary extensional basin developed in northeast Iberia during the Mesozoic period, registered a widespread long-term marine regression during the Campanian–Maastrichtian. This latest Cretaceous regression was mostly related to the initial stages of inversion of the Iberian Basin due to the onset of the convergence of Africa–Europe–Iberia (e.g. Segura et al., 2004; Martín-Chivelet et al., 2019; Aurell et al., 2022). As a result, the shallow marine carbonate environments that dominated the Iberian Basin during most of the Late Cretaceous turned progressively into coastal and continental settings.

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This progressive change to continental depositional environments included development of palustrine carbonate systems in coastal marine settings along some marginal areas of the Iberian Basin (e.g. Platt, 1989; Martín-Chivelet and Giménez, 1992).

Several Campanian units with frequent carbonate-dominated palustrine–lacustrine intervals are found across different domains of the Iberian Basin, such as the Sierra Perenchiza in the South Iberian domain, the Santo Domingo de Silos, Santibañez del Val and Sierra de la Pica formations in the Castillian domain, and the Fortanete Fm in the Maestrazgo domain. Previous research on these units provided the general stratigraphical and sedimentological context (e.g. Canerot et al., 1982; Almunia et al., 1985; Vilas et al., 1982; Almunia et al., 1985; Floquet, 1991; Martín-Chivelet and Giménez, 1992; Martín-Chivelet et al., 2019).

This study focusses on the lower Campanian successions of the Fortanete Formation. This formation represents a previously unexplored unit corresponding to a low-gradient slope lacustrine–palustrine carbonate environment with intermittent marine influence. The main objectives of the present study of the Fortanete Fm are: (1) to perform a complete stratigraphic and sedimentological study with the reconstruction of a synthetic palaeoenvironmental model and study of the lateral variations between the different studied areas; (2) to describe macro- and microfeatures found in the carbonate palustrine succession and interpret their genesis; (3) to analyse the climatic, tectonic, topographic and hydrologic processes that could take part in the evolution and formation of this lacustrine/palustrine system and understand some of the main processes affecting the region during the lower Campanian; and (4) to use the published examples for comparison of the Fortanete Fm with both modern and ancient analogues to decipher processes controlling palustrine environments in the past.

2. Geological setting

Extensional tectonics was linked with Atlantic and western Tethys Ocean transgressions, which controlled the palaeogeographic evolution of the eastern Iberian Plate during most of the Mesozoic period. The initial Late Permian to Early Triassic rifting phase resulted in the formation of the main sedimentary basin developed under the extensional regime, the NW–SE intracratonic Iberian Basin (e.g. Arche and López-Gómez, 1996; Sánchez-Moya and Sopeña, 2004). Further tectonic compartmentalisation along the Iberian Basin occurred during latest Jurassic–Early Cretaceous due to a second episode of rifting (e.g. Salas et al., 2001; Aurell et al., 2019; Martín-Chivelet et al., 2019). A Late Cretaceous post-rift stage involved the expansion and homogenisation of the depositional areas in the Iberian Basin and resulted in the setting of a large carbonate epeiric platform bounded by the emerged Iberian and Ebro massifs (Fig. 1A; Feuillée, 1967; Floquet, 1991).

During the Late Cretaceous, the palaeolatitude of the Iberian Basin was of 25°N–30°N (Dercourt et al., 2000). The climate was controlled by the subtropical high-pressure belt and the equatorial system of ocean currents and it fluctuated from arid to sub-humid in mainly hot conditions (e.g. Skelton, 2003; Stampfli and Kozur, 2006; Hay and Floegel, 2012; Martín-Chivelet et al., 2019). Two large marine domains of the Upper Cretaceous Iberian epeiric platform opened towards the Bay of Biscay and the Tethys Sea in the Castilian and the South Iberian ramps respectively (Fig. 1A; Martín-Chivelet et al., 2019). The tectonic subsidence in the Iberian Basin during the Cenomanian to Santonian interval favoured the development of locally subsiding areas, also controlling the presence of episodic marine transgressions (Alonso et al., 1993; Segura et al., 2001; Gil et al., 2004, 2006). Moreover, long-term sea level fluctuations influenced the sedimentation of the basin in the Castilian ramp (Floquet et al., 1982; Gräfe, 1994, 1999; Floquet, 1991, 1998, 2004; Segura et al., 2001, 2014; Baceta et al., 2004), and in the South Iberian ramp (Martín-Chivelet and Giménez, 1992; Martín-Chivelet, 1995, 2003), resulting in a second order transgressive–regressive cycle covering Mid-Turonian to Campanian. Around the transgressive peak of this cycle, during the end of the Santonian, coastal to shallow-marine carbonate platform successions with rudist-rich levels dominated the Northwest and Southeast regions of the basin (e.g. Torromé et al., 2022). However, during the early Campanian, the most southern areas of the South Iberian domain were dominated by coastal and continental sedimentation represented by the Sierra de Perenchiza and Villalba de la Sierra formations in locally subsiding subbasins. On the other hand, shallow-marine and coastal environments dominated in the central and northern areas of the basin (Fig. 1B; Floquet, 1991; Segura et al., 2004; Martín-Chivelet et al., 2019; Aurell et al., 2022).

The lower Campanian succession recorded in the eastern margin of the Iberian Basin studied here (i.e. the Maestrazgo domain) is represented by continental carbonates, evaporites, marls and clays of the Fortanete Fm (Fig. 2A). The overall thickness of this unit ranges be-

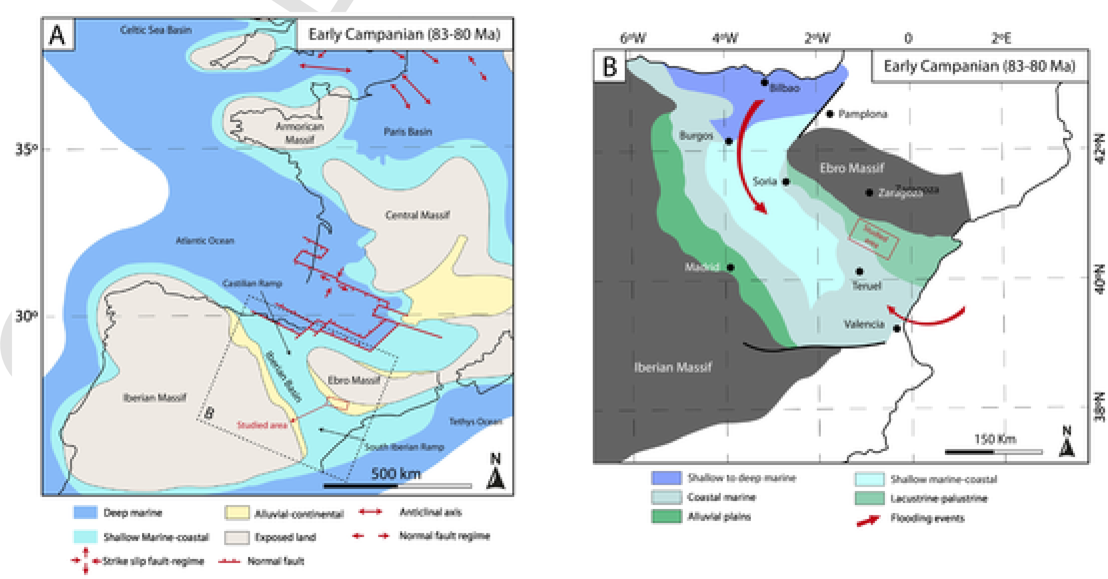


Fig. 1. (A) Palaeogeography of southwestern Europe during the early Campanian (modified from Dercourt et al., 2000). (B) Distribution of the main palaeogeographic domains in the Iberian Basin during the early Campanian (compiled from Floquet, 1991; Segura et al., 2004; García et al., 2004 and Martín-Chivelet et al., 2019).

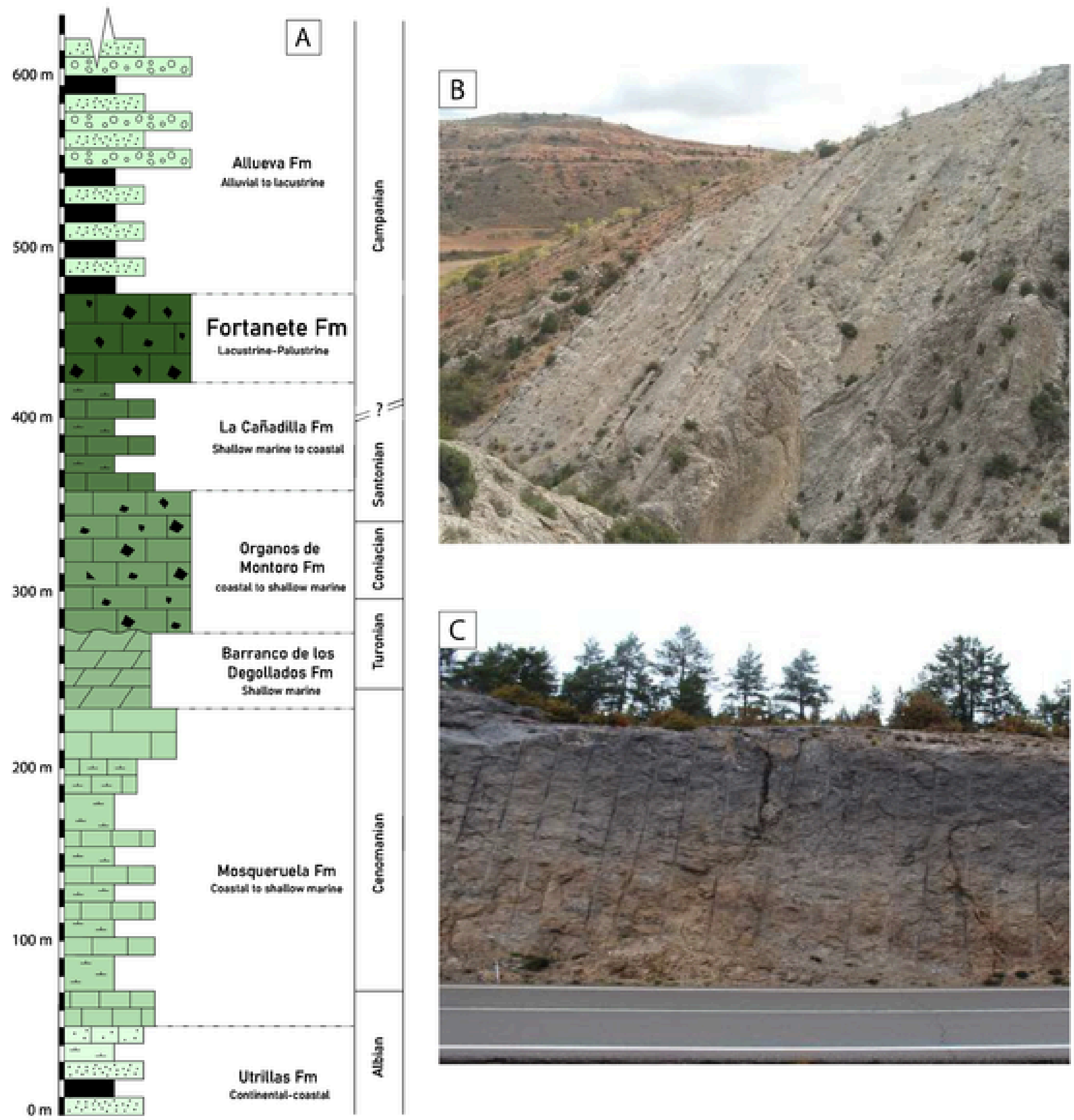


Fig. 2. (A) Synthetic stratigraphic log of the uppermost Cretaceous of the study area (modified after Torromé et al., 2022). (B) Panoramic view of the Cosa log showing a well stratified section of limestones and marly-limestones of the Fortanete Fm. (C) Outcrop view of the Fortanete log showing the more typical massive and brecciated aspect of the limestones of the Fortanete Fm.

tween 20 and 100 m. The Fortanete Fm consists of stratified intercalations of m-thick limestones and charophyte-rich marls (Fig. 2B), and massive brecciated burrowed limestones with gastropods (Fig. 2C). The lower boundary of the Fortanete Fm represents the final stages of a major regressive event around the Santonian–Early Campanian (Fig. 2A), with the progressive setting of continental carbonates over the coastal and shallow marine limestones and marls with rudists, foraminifera and dasycladacean algae of the La Cañadilla Fm. However, the La Cañadilla Fm also includes peritidal features in the shallowing upwards high-frequency sequences, with levels of supratidal breccias rich in gastropods and charophytes similar to those dominant in the Fortanete Fm (Torromé et al., 2022). The upper boundary of the Fortanete Fm is defined by an abrupt lithological change, from continental limestones to the reddish alluvial claystones, sandstones and conglomerates of the overlying Allueva Fm (Fig. 2A). This boundary corresponds to a depositional hiatus of uncertain amplitude, that occurred at the onset of the middle Campanian (Aurell et al., 2022).

Magneto- and biostratigraphic data of the Fortanete Fm indicate that it was mostly deposited during the early Campanian (i.e. subchron C33r; Aurell et al., 2022). This age assignment fits the middle Santonian–earliest Campanian age proposed in Torromé et al. (2022) for the underlying La Cañadilla Fm based on biostratigraphic and Sr-isotopic data. The palaeogeographic setting of the northeast Iberia (Fig. 1B) does not allow discarding the possibility of combined Atlantic and Tethyan incursions reaching the study area during the early Campanian. However, Torromé et al. (2022) suggested a major influence from the Tethys Ocean in the area around the Santonian–Campanian instead of Atlantic influence.

3. Materials and methods

The Fortanete Fm has been studied in a 40 km wide and 80 km long area located in the northeastern Iberian Chain (Fig. 3). A total of 10 stratigraphic sections have been logged, with an average distance of 13 km between sections (Fig. 4A). The thickness of the unit is variable, ranging between 20 and 30 m in the western areas and between 45 and 100 to the east. Aiming to achieve a detailed analysis of a unit affected by subaerial exposure and pedogenic modification, additional sample collection was done in the Fortanete section, along a road cut perfectly exposing almost 50 m-thick unit of brecciated limestone in the lower part of the Fortanete Fm (Fig. 2C).

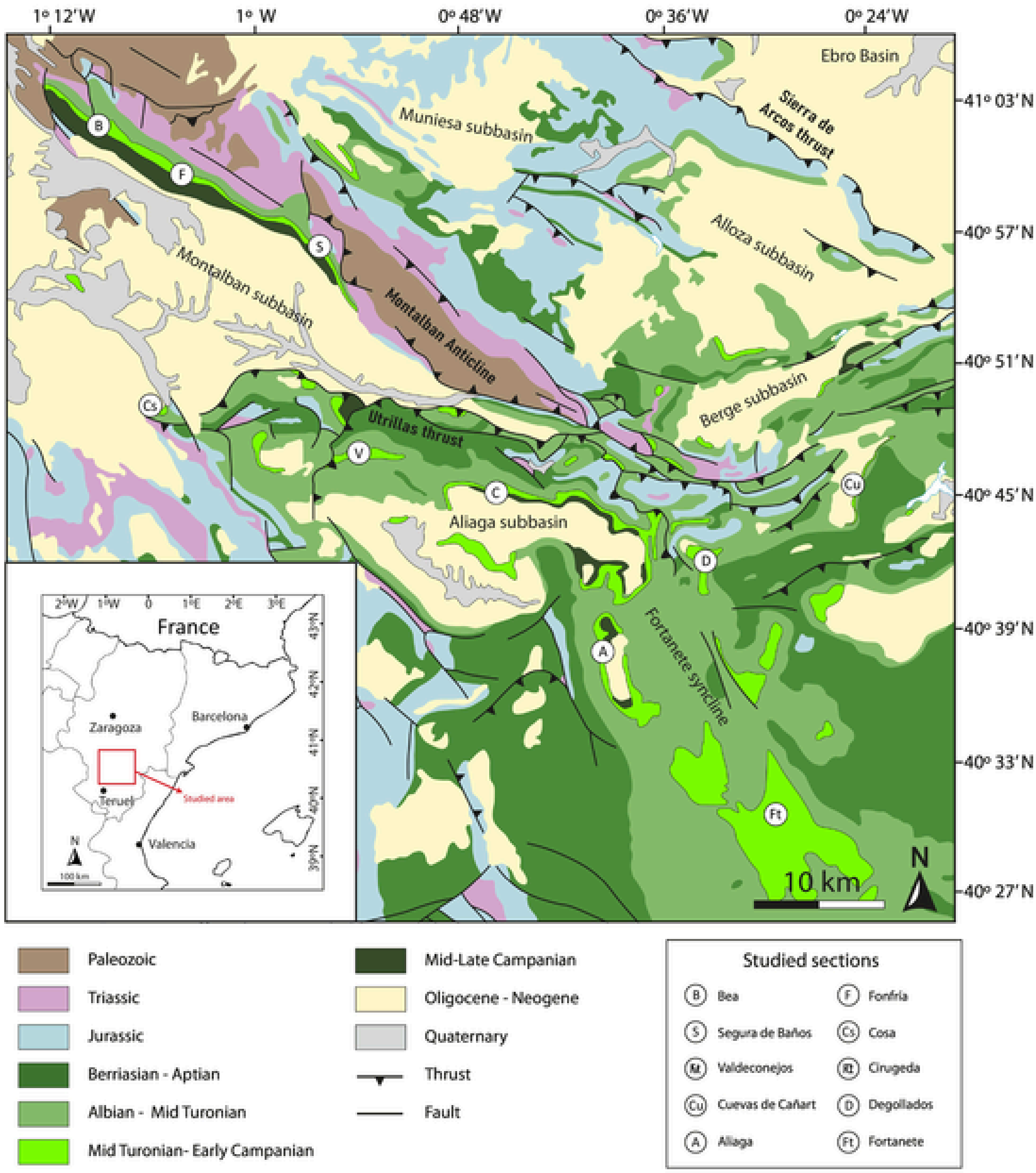


Fig. 3. Geological map of the study area (modified after Aurell et al., 2022). The map shows the location of the 10 studied stratigraphic logs.

Facies description was done taking into account both field observations (bedding, lithology, texture, components and sedimentary structures) and samples. Petrographic characteristics were observed in 145 samples of limestone (66 polished slabs and 79 thin sections) and 17 samples of marl. Polished slabs were described using a binocular microscope, and thin sections (30–50 μm) were examined using an Olympus BX51 polarising microscope equipped with an Olympus SC50 digital camera. The amount of $CaCO_3$ in marls was determined by calcimetry. Textural classification follows the Dunham (1962) scheme, whilst description of non-skeletal grains is based on Flügel and Munnecke (2010). Palustrine facies and microfabric were described using works of Freytet and Plaziat (1982), Alonso-Zarza (2003) and Alonso-Zarza and Wright (2010).

Semi-quantitative elemental composition of relevant features in thin sections has been analysed at the Laboratory of Microscopy ZRC SAZU, Ljubljana, using a JEOL JSM-IT100 scanning electron microscope (SEM) equipped with an Energy Dispersive X-ray Spectroscopy (EDS) detector. Thin sections were mounted with carbon tape onto aluminium stubs and examined in two different ways: a) uncoated samples were analysed under low vacuum (40 Pa) and b) samples coated with carbon using a JEOL JEC-530 coater were observed under high vacuum. In both cases observations were made at an accelerating voltage of 15 kV and a working distance of 10 mm. Images were taken in topographic backscattered electron imaging mode (BES). Qualitative and semi-quantitative elemental analyses (EDS) have been performed in the low and high-vacuum conditions.

The $\delta^{13}C$ and $\delta^{18}O$ isotope analysis has been carried out for 23 carbonate samples from the Fortanete section. Samples were carefully selected from thin section slabs under a binocular microscope in order to avoid microfractures, cements, extraclasts, etc. An amount of ~0.1 g of sample powder was obtained by crashing rocks using a pestle and stored in Eppendorf tubes after being sieved to obtain powder of 53 μm. To obtain the isotopic relations $^{13}C/^{12}C$ and $^{18}O/^{16}O$, CO_2 was obtained by reaction with H_3PO_4 (103 % and 90 °C) with the ISOCARB system. CO_2 was analysed by mass spectrometry (SIRA-II model) in Dual Inlet

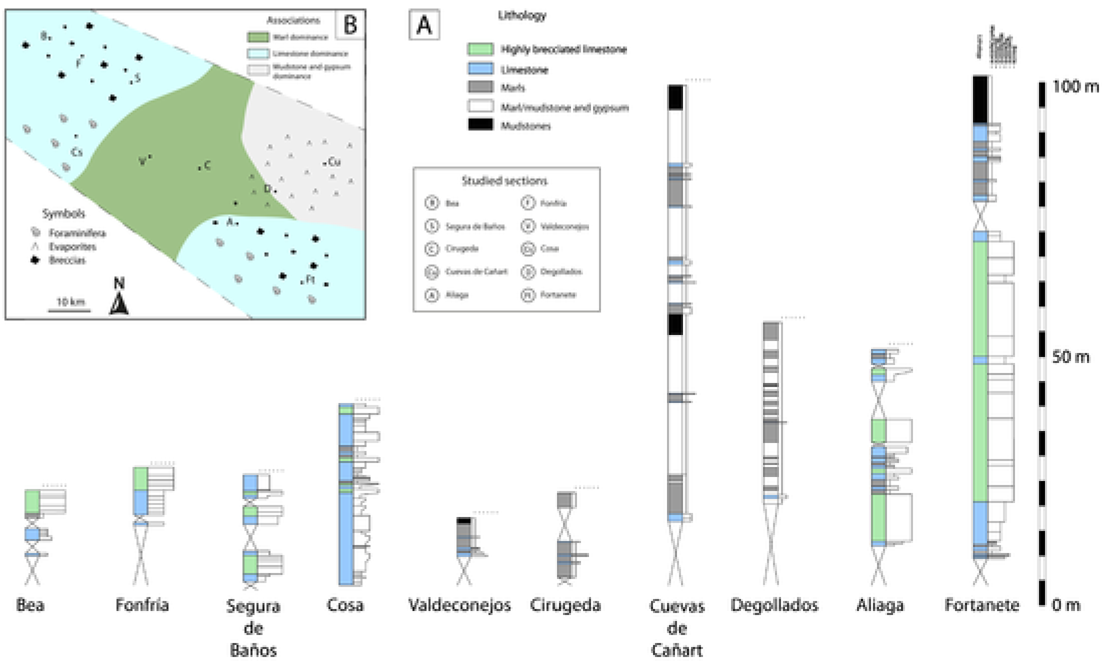


Fig. 4. (A) Schematic representation of the 10 studied stratigraphic logs, indicating the lithology, thickness and texture (after Dunham, 1962) of the different levels. (B) Lithofacies distribution map reconstructed for the study area based on each lithofacies dominance and sedimentary features.

mode. This analysis was performed by the "Servicio de análisis de isótopos estables" at the University of Salamanca.

4. Facies analysis

The Fortanete Fm includes a wide spectrum of lithofacies (F1 to F8), including marls, mudstones with evaporites, and limestones. Main components and sedimentary structures differentiated along the 8 facies can be seen in Fig. 5.

4.1. Facies description

Limestone facies F1 (bioclastic wackestone–packestone; Fig. 6A–D) mainly consists of dm- to m-thick wackestones with some local packstone accumulations, and in some levels mudstone textures. The most common components are characean algal gyrogonites and in minor proportion, stems (Fig. 6A, B) and gastropod fragments (*Lychnus* sp.). Facies F1 is characterised by fenestral fabric and small cylindric burrows cm-size. Secondary elements are isolated pebbles, fragmented bivalves, and locally (in Fortanete, Aliaga and Cosa sections) foraminiferal assemblage consisting of miliolids (Fig. 6C) and rare discorbids (rotaliids, Fig. 6D).

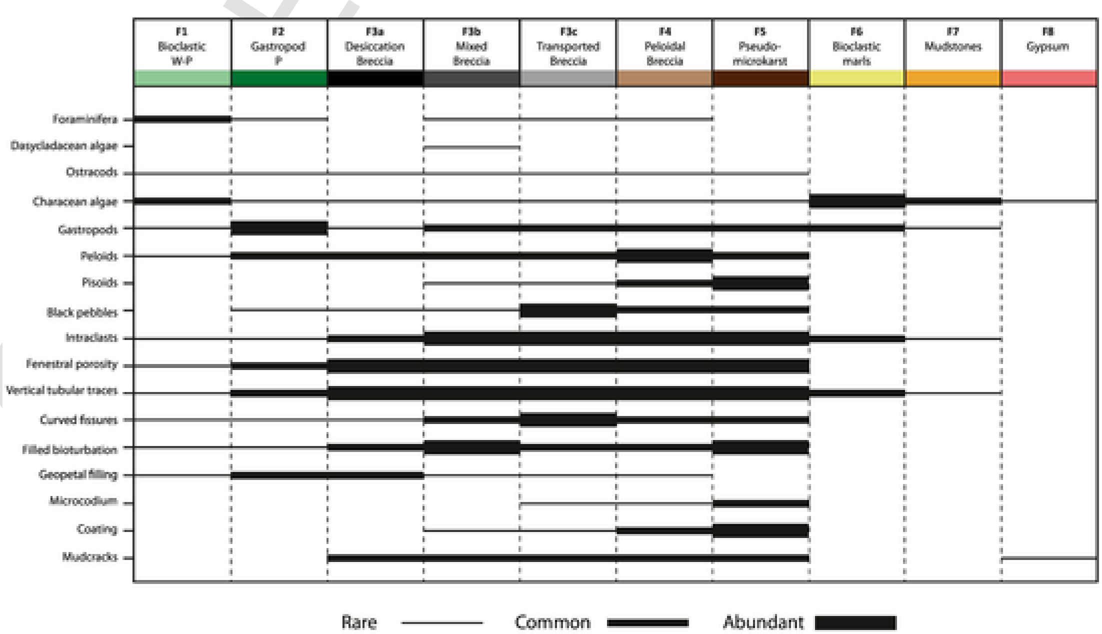


Fig. 5. Facies table for the 5 defined facies in limestone levels, with the distribution and relative abundance of components (skeletal and non-skeletal) and main sedimentary structures.

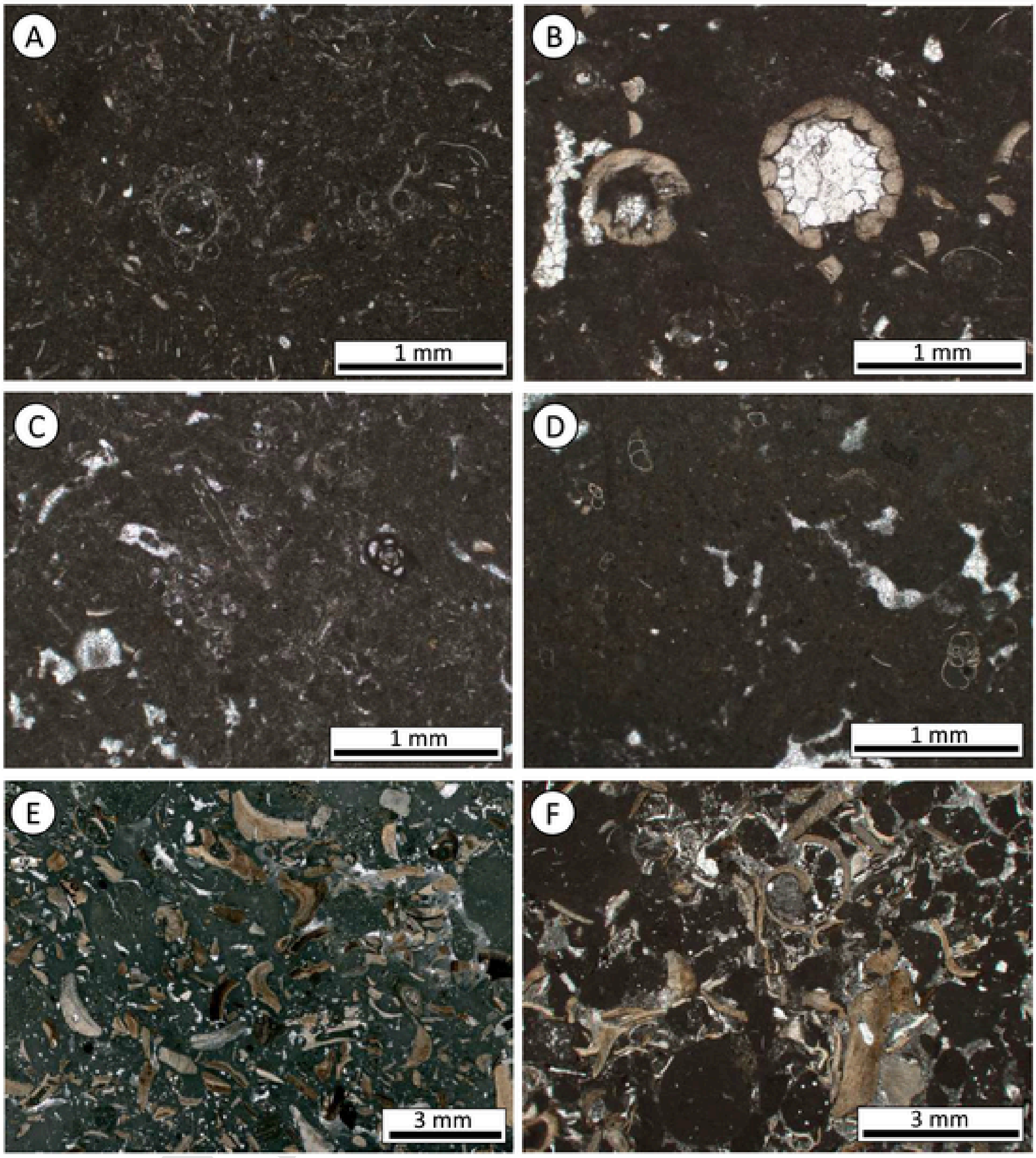


Fig. 6. (A) Thin section image of charophyte stems, most of them fragmented and dispersed in a micritic matrix (F1, Cuevas de Cañart). (B) Thin section image of well-preserved charophyte gyrogonites, some fragments are also visible (F1, Fortanete). (C) Thin section image of an isolated miliolid in a micritic matrix (F1, Cosa). (D) Thin section image of dispersed rotaliids floating in a micritic matrix showing small patterns of fenestral porosity (F1, Cosa). (E) Thin section image of a packstone accumulation of gastropod fragments of different sizes (F2, Aliaga). (F) Thin section image of a packstone accumulation of gastropod fragments and well-rounded micritic peloids (F2, Cosa). All microphotographs taken under plane polarised light (PPL).

Limestone facies F2 (gastropod packstone; Fig. 6E, F) is found locally and isolated, arranged in irregular beds 0.5 to 3 m-thick, it contains scarce characean algae but abundance of fragmented gastropods accumulated in a mud-dominated matrix (Fig. 6E). Fragments of consolidate sediment reworked from within the area of deposition are common (Fig. 6F) and defined as intraclasts after Folk (1959). Rounded to subrounded micrite structureless sand-sized grains can be also found in this facies, and defined as peloids after Flügel and Munnecke (2010). Fenestral fabric is also a characteristic feature of this facies.

Brecciated limestone facies (F3) (Figs. 5, 7A, B) is subdivided into 3 subfacies (F3a, F3b, F3c) depending on the intensity of fragmentation processes and transport, resulting in different breccia features and patterns, most of them described by Freytet and Plaziat (1982).

Subfacies F3a (desiccation breccia) consists of 2 to 3 m-thick tabular-bedded and massive limestone bodies. Skeletal grains are scarce and consist of ostracods, characean algae and gastropods. The main component is large angular, intensely fissured intraclasts (Fig. 7C). This type of breccia appears to be mostly affected by desiccation and transport evidences are scarce or absent.

Subfacies F3b (mixed breccia) appears in m-thick massive and tabular units and consist of limestone breccia showing moderate levels of desiccation and transport (Fig. 7D). It is normally associated with filling of large desiccation vertical traces. Clasts that compose the filling are sub-angular to angular and have the same composition as the matrix.

Subfacies F3c (transported breccia; Fig. 7E) is arranged in m-thick massive and tabular limestone displaying common vertical features. Gastropods (mainly *Lychnus* sp.) are common and can be partially fragmented or well preserved. Characean algae, ostracods and isolated foraminifera appear in minor proportion. Vertical traces are commonly filled by rounded peloids and intraclasts of diverse origin. Black pebbles, defined as reworked carbonate lithoclasts with a distinct dark grey colouration (Strasser, 1984), are very common in this facies (8B, 8E).

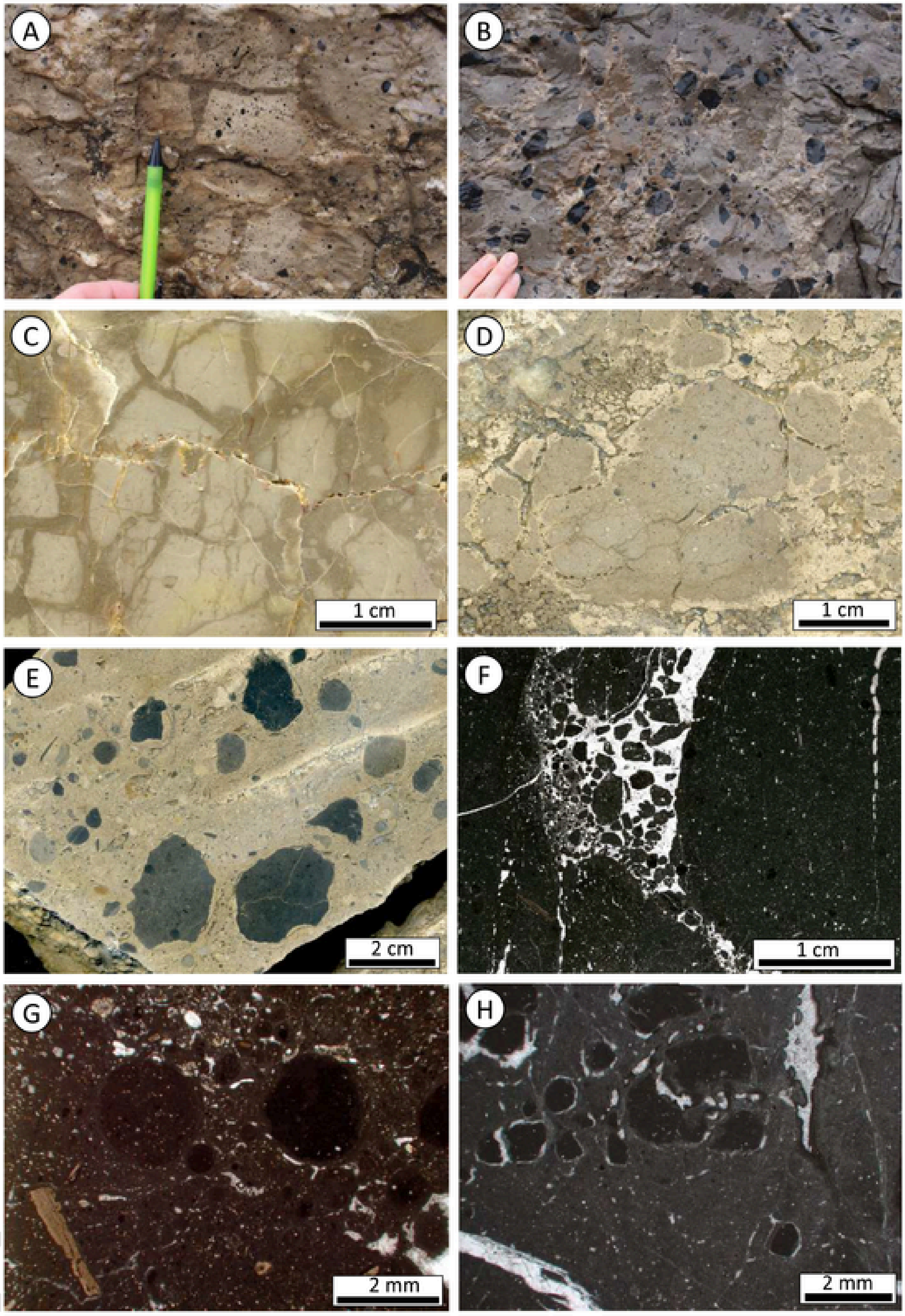


Fig. 7. (A) Outcrop view of a polygenetic breccia (Fortanete). (B) Outcrop view of an accumulation of black pebbles with mostly vertical and subvertical irregular structures (Fortanete). (C) Polished slab picture of a desiccation breccia, mutual relationships between fractures are still recognisable (subfacies 3a, Segura de Baños). (D) Polished slab picture of a desiccation and transport breccia (subfacies 3b, Fortanete). (E) Polished slab picture of a polygenetic breccia showing different types of black pebbles in terms of colour, size and roundness (subfacies 3c, Fortanete). (F) Thin section image (PPL) of a desiccation and transport breccia whose filling components present the same texture as the matrix (Fortanete). (G) Thin section image (PPL) of rounded nodules in a micritic matrix that shows fenestral porosity cemented by drusy mosaics of calcite. In the upper part of the image we can see ostracods and *Microcodium* rosettes (Fortanete). (H) Thin section image (PPL) of circumgranular cracks around nodules dispersed in a micritic matrix. Cracks and fenestral porosity (on the right) are filled with drusy calcite cements (Segura de Baños).

Black pebbles in the Fortanete Fm range in size from mm to cm and show sub-angular to well-rounded morphology.

Vertical and subvertical cylindrical and irregularly shaped structures (Fig. 7B) are recognisable in all the studied profiles but absolutely prevail in facies F3. These structures consist of voids, mm to cm wide and up to a few decimetres long. In most cases, the voids are wider towards the top of the beds and decrease in diameter downwards, rarely exhibiting bifurcating patterns. The void filling is composed of intraclasts (Fig. 7F) and peloids surrounded by calcite cements.

Another common grain in F3 are small and well-rounded dark grains that display a diffuse margin and similar fabrics as the surrounding matrix (Fig. 7G, H). These grains are comparable to blackened pedogenic micronodules described by Martín-Chivelet and Giménez (1992) which do not show considerable difference in internal fabric from the matrix and are slightly darker than the surrounding matrix but not as dark as black pebbles. They are mostly rounded to sub-rounded in shape and range in size from less than a millimetre to no more than a centimetre. These nodules are elementary nodules as classified by Freytet and Plaziat (1982). When these nodules are reworked, it is difficult to differentiate them from other limestone intraclasts.

Facies 4 (peloidal breccia) includes limestones arranged in m-thick tabular to irregular beds commonly showing cm-size tubular to irregular vertical structures (traces or sediment-filled root moulds according to Alonso-Zarza and Wright (2010)), desiccation voids and fenestral fabric. Peloids are the predominant component, followed by pisoids, intraclasts and black pebbles. Pisoids are defined after Peryt (1983) and Flügel and Munnecke (2010) as mm-sized micritic grains with non-marine origin and coated. Gastropods (*Lychnus* sp.) are abundant and usually appear non-fragmented. Other fossils are foraminifera, ostracods and characean algae (Figs. 5, 8).

The main feature in facies F4 is fenestral fabric, one of the most common expressions of planar voids caused by internal fracturing of

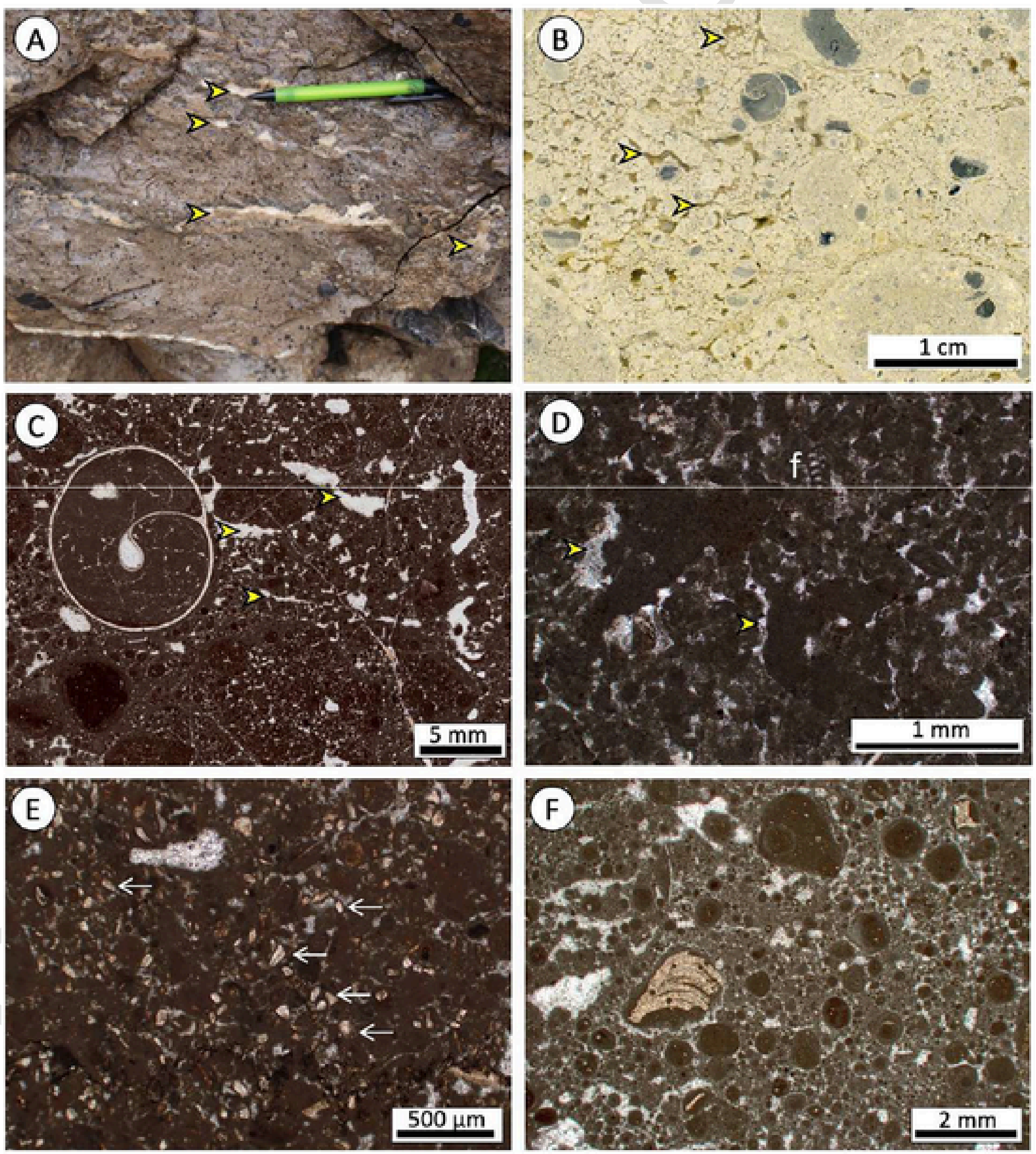


Fig. 8. (A) Outcrop view of elongated fenestral-like planar voids filled by cement (Fortanete). (B) Polished slab picture of an accumulation of peloids due to extreme development of fenestral porosity (Fortanete). (C–D) Thin section images (PPL) of chaotic patterns of extreme fenestral porosity causing the formation of peloidal accumulations along with a gastropod (C) and foraminifera (D) (C — Fortanete; D — Cosa). (E) Thin section image (PPL) of a peloidal accumulation presenting a lot of reworked grains of *Microcodium* (Fortanete). (F) Thin section image (PPL) of an accumulation of pisoids showing simple micritic coating (Fortanete). Yellow arrows point to examples of fenestral porosity, white arrows point to reworked grains of *Microcodium*.

fine-grained material (Freytet and Plaziat, 1982). It can be recognised at the macroscale in the field, forming elongated cement-filled cavities, several mm wide with irregular and non-parallel walls (Fig. 8A) (Brewer, 1964). At the microscale, fenestral fabric displays irregular patterns of pores (Fig. 8B and C) filled by a variety of cements, from occasional geopetal fillings and micritic vadose cements, to isopachous fringe cements and more common drusy and blocky mosaics of calcite spar and microspar (Fig. 8D–F).

Facies F5 (limestone with pseudomicrokarst) is distinguished by the abundance of vertical and horizontal voids, cylindrical or irregular in shape, and cm- to dm-long and cm-wide (Fig. 9A). The voids have irregular or smooth boundaries. They can be small and isolated, or interconnected, forming complex void systems. Pseudomicrokarst cavity fills are variable and complex. Major parts of cavities are filled by pisoids, peloids, small intraclasts, scarce bioclasts, and blocky calcite cement (Fig. 9B). Typical vadose cements can be seen such as pendant or meniscus (Fig. 9E), and some isolated isopachous forms represent phreatic cementation. SEM elemental composition of all cements indicates low Mg-calcite (LMC) mineralogy (Fig. 11B). The void infill can exhibit the same composition and fabric (Fig. 9C, D) as the matrix or can differ significantly, thus indicating variable and polygenetic origin of the sediment, originating from the surface and walls or reworked from distant sediment sources. Peloids (Fig. 9E) are another common type of filling and consist of rounded to sub-angular mm-size grains surrounded by calcite cement. The pisoidal coating, analysed in SEM EDS, shows no difference in composition with respect to the matrix, and is formed only by a thin layer of micrite.

Facies F6 (bioclastic marls) consists of marl deposits that are normally 1 to 3 m-thick, but may form up to 5 m-thick intervals (Fig. 10A, B). Fossil content mainly consists of highly fragmented continental gastropods (in particular, large fragments of *Lychnus* sp.), and charophytes. Charophyte remains are very abundant, reaching exuberant propor-

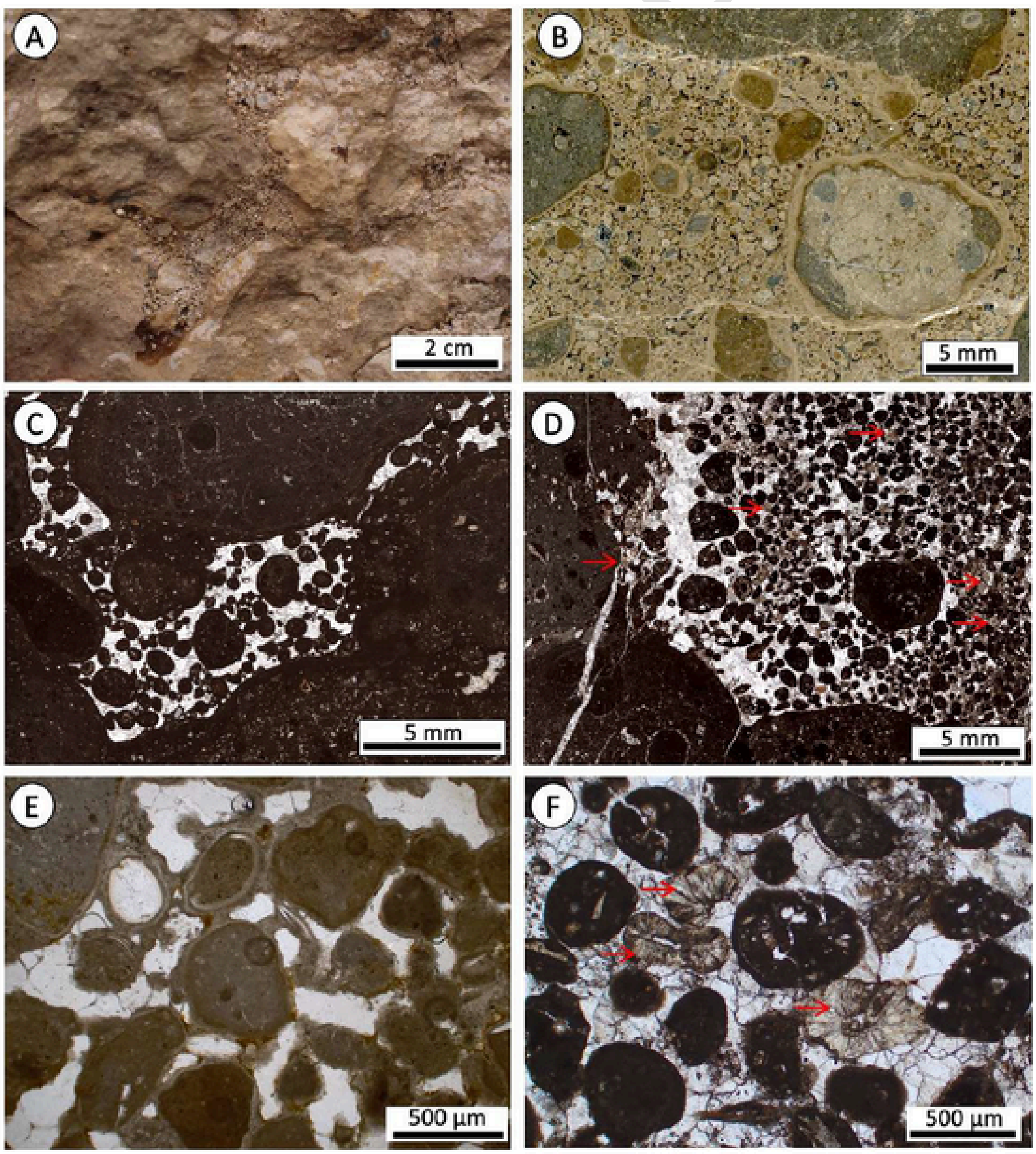


Fig. 9. (A) Outcrop view of connected galleries of pseudomicrokarst that are filled by pisoids and intraclasts. (B) Polished slab picture showing the typical filling found in pseudomicrokarst galleries, consisting on coated intraclasts and pisoids. (C–D) Thin section images (PPL) of filled galleries of pseudomicrokarst, consisting in peloids (C) and peloids with well-preserved *Microcodium* (D). (E) Peloids and ostracods surrounded by meniscus microcrystalline calcite cements and a later blocky calcite cement. (F) *Microcodium*-peloidal accumulations surrounded by blocky calcite cement. All pictures shown in this figure belong to samples taken from the Fortanete section. Red arrows point to examples of *Microcodium*.

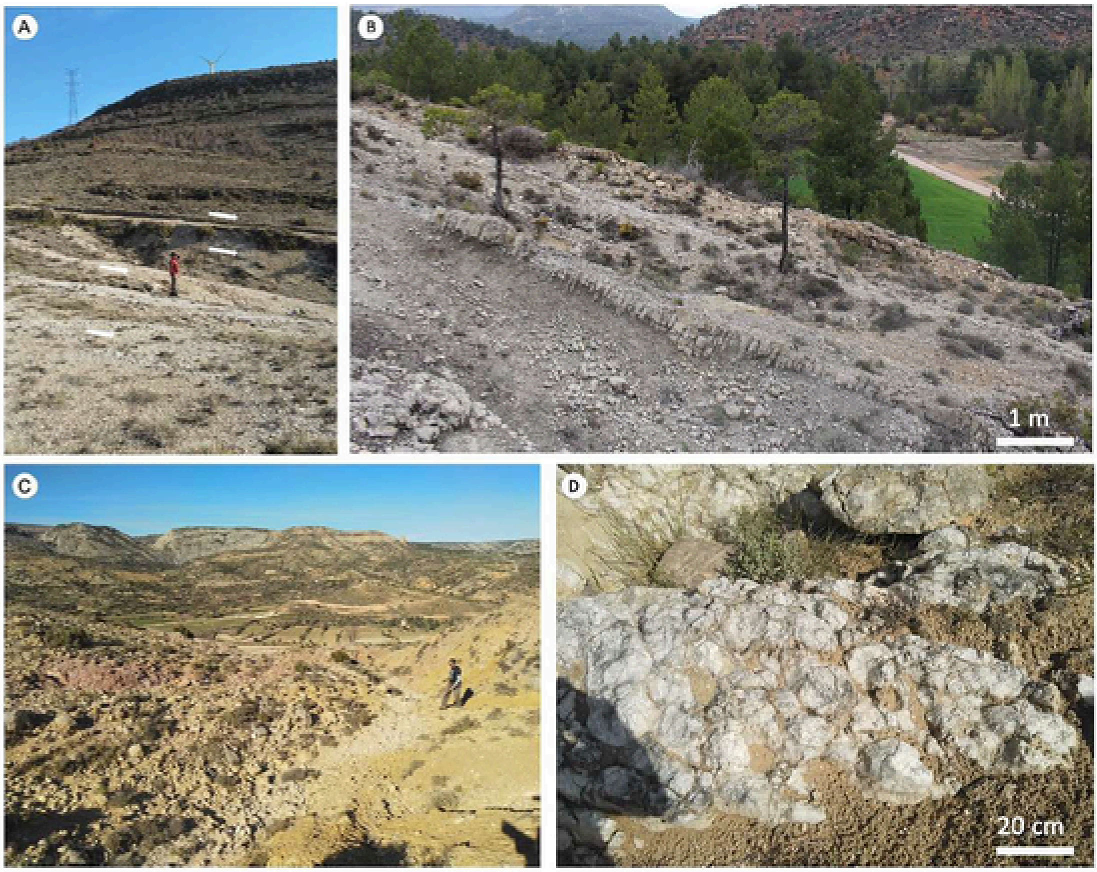


Fig. 10. (A) Field view of m-thick deposits of light-grey marls (Valdeconejos; arrows point to marls). (B) Field view of an intercalation of limestone beds and dark grey marls (Aliaga). (C) Field view of m-thick deposits of yellow, white and reddish mudstones (Cuevas de Cañart). (D) Outcrop view of nodular gypsum embedded in a brownish mudstone (Degollados).

tions of gyrogonites in some levels, but characterised by low diversity and relatively small size of gyrogonites (Sphaerochara and Strobilochara). In a few of the analysed marl samples, charophyte stems are also preserved. $CaCO_3$ contents of the marl deposits range between 30 and 60 %.

Facies F7 (mudstone) is characterised by levels of m-thick (up to 10 m) reddish to yellowish mudstone with less than 20 % of calcium carbonate (Fig. 10C). They locally contain remains of characean algal gyrogonites and highly fragmented gastropods. Some vertical traces and intraclasts can also be found.

Finally, facies F8 (gypsum) consists of evaporites arranged in highly irregular beds of nodular gypsum, 0.5 to 2 m-thick (Fig. 10D), and also appears as numerous thin, cm-thick gypsum veins inside thick yellowish and reddish mudstone deposits. The only fossils associated with evaporites are highly deformed characean gyrogonites. Desiccation cracks can be found.

4.2. Facies associations

Predominance of lithofacies along with the sedimentary and subaerial exposure and post-depositional modification features allowed differentiation of three subenvironments (Fig. 4B) associated with three facies associations. Predominance of marls corresponds to lacustrine areas (lacustrine facies association), mudstone-evaporite lithofacies to mudflat settings (mudflat facies association), whereas successions, mainly composed of limestone facies, represent palustrine areas, strongly affected by subaerial exposure, reworking and pedogenic processes (palustrine facies association).

4.2.1. Lacustrine facies association

Marls from facies F6 are found across all the logged sections, being especially dominant in the central areas of the basin, in Valdeconejos and Cirugeda sections (Fig. 4). Marl levels in this area are m-thick (up to 4 m) and present some thin limestone bed intercalations (Fig. 10B) belonging to facies F1 (bioclastic wackestone–packstone). In some isolated cases, irregular dm-thick packstone accumulations of fragmented gastropods from facies F2 appear. Locally, in Valdeconejos, levels of marls pass gradually to mudstones (F7) with a significant amount of charophytes.

4.2.2. Mudflat facies association

Facies 7 (mudstones) and 8 (gypsum) are dominant in the northeastern areas, around the Degollados and Cuevas de Cañart sections (Fig. 4). In Cuevas de Cañart, the thickest deposits consist of bioclastic marls from F6 (30–40 $CaCO_3$ %) passing vertically to m-thick deposits of mudstones (F7) with intercalations of numerous thin-veins of gypsum (F8). This association can reach up to 20 m-thick. Some levels of pure mudstone, with no gypsum associated, are found and present very low quantity of fossiliferous content, which mainly consist in charophyte gyrogonites.

In Degollados gypsum levels are nodular and thick, intercalating with bioclastic marls rich in charophytes. Finally, along both sections, isolated, mostly dm-thick levels of limestones from F1 appear. In addition, *Lychnus* sp. and charophytes can be observed.

4.2.3. Palustrine facies association

Massive to poorly bedded limestones are the most characteristic lithofacies of the Fortanete Fm and the main focus of this study. These carbonates are concentrated in two separate areas located northwest and southeast respectively (limestone dominance, Fig. 4). The limestones in these areas include a wide spectrum of facies, however, F3 to F5 highly dominate.

In the northwestern areas of the basin (Bea, Fonfría and Segura de Baños sections), there is also significant presence of facies F1 and F2, which gradually passes vertically to F3–F5 facies in 10–15 m-thick successions. F6 marls appear but are mostly covered, however, the few levels that were sampled showed a big amount of charophytes. Cosa, despite being in the same subenvironment area, displays a bit different pattern, which is high dominance of bioclastic F1–F2 limestones in massive m-thick beds, intercalating with thinner levels of marls and F3–F5.

The absolute predominance of F3–F5 is clearer in the southeastern localities of Aliaga and Fortanete. A few dm-thick levels of F1 facies drastically change to m-thick massive brecciated limestone from F3, F4 and F5. At the end of the logged sections, few intercalations of F6 marls and F1–F2 announce the end of the brecciated intervals.

4.3. Subaerial exposure and post-depositional modification features (F3–F5)

F1 and F2 represent depositional facies, whereas F3 to F5 are characterised by features indicating modification during subaerial exposure and sediment alteration that overprinted most of their primary characteristics. The study of the previously described features led to the interpretation of the processes forming them.

Plant roots probably played an important role in generation of both macro- and microfeatures. Brecciation can result from physical disruption by root growth (Klappa, 1980) or due to tree heave (Semeniuk, 1986). Brecciation can also be caused by the displacive growth of carbonate, wetting and drying cycles, thermal expansion and swelling clays (Wright and Tucker, 1991).

Facies F3 commonly shows very well-developed desiccation patterns characteristic of palustrine sediments (Freytet and Plaziat, 1982) but also of peritidal carbonates (Shinn, 1983; Pratt, 2010). Irregular and horizontal planar pores formed by shrinkage are associated with desiccation processes due to periodic subaerial exposure. Brecciated beds show evidence of desiccation processes in higher proportion than the rest of described facies. Shrinkage of sediments after periodical exposure led to fragmentation of the original matrix and developing of intraclasts (Braithwaite, 2005). Precipitation of cement in the formed pores can lead to expansion and breakage of sediments, contributing to the brecciation process (Watts, 1978; Arakel, 1982; Buczynsky and Chafetz, 1987; Braithwaite, 1989).

Facies 3a desiccation fissures indicate in-situ generation of intraclasts and formation of a new matrix surrounding them. The clasts of the same composition are only locally displaced and are delineated by interconnected fractures and fissures. On the other hand, facies 3b indicates transport on short distances (e.g. desiccation led to falling of broken sediment from the upper levels into the fractures). Finally, facies 3c presents different composition clasts from the surrounding matrix and is sub-rounded to well-rounded in shape, indicating longer-distance transport. Breccias from facies 3c are commonly polygenetic, composed of clasts of different origin (Fig. 7A).

Along with intraclasts formed by desiccation and bioturbation, other common grains found in breccias are black pebbles (Fig. 7B, E) and nodules (Fig. 7G, H). Black pebbles have been also recognised southwards, in the Sierra de Utiel Fm, as coming from a blackened surface rich in organic matter affected by desiccation cracks or other types of porosity (Martín-Chivelet and Giménez, 1992). Black pebbles (blackened clasts) can form by different processes of carbonate sediment staining and reworking, most commonly at subaerial exposure surfaces but also in organic-rich lacustrine and marine environments. Dark grey or black colouration of carbonate material can originate from incorporation of terrestrial organic matter or can be due to impregnation of sediment by organic substances in shallow subaqueous anoxic microenvironments (Strasser, 1984). Dark staining of carbonate clasts observed in Quaternary subaerially-exposed carbonates has been also attributed to burning in periodic fires (Shinn and Lidz, 1987; Platt and Wright, 1992).

Regarding nodules (also termed glaebules), their genesis can be related to concentrations of Fe^{3+}-enriched carbonate (Freytet, 1973; Martín-Chivelet and Giménez, 1992), however, SEM EDS analysis has not shown a detectable amount of iron (Fig. 11A), although minor amounts of Fe probably gave some carbonate nodules reddish tones. Differential lithification in porous areas induces a textural separation (Alonso-Zarza and Wright, 2010) that is only reinforced by other processes such as cracking around the nodules due to desiccation (Martín-Chivelet and Giménez, 1992).

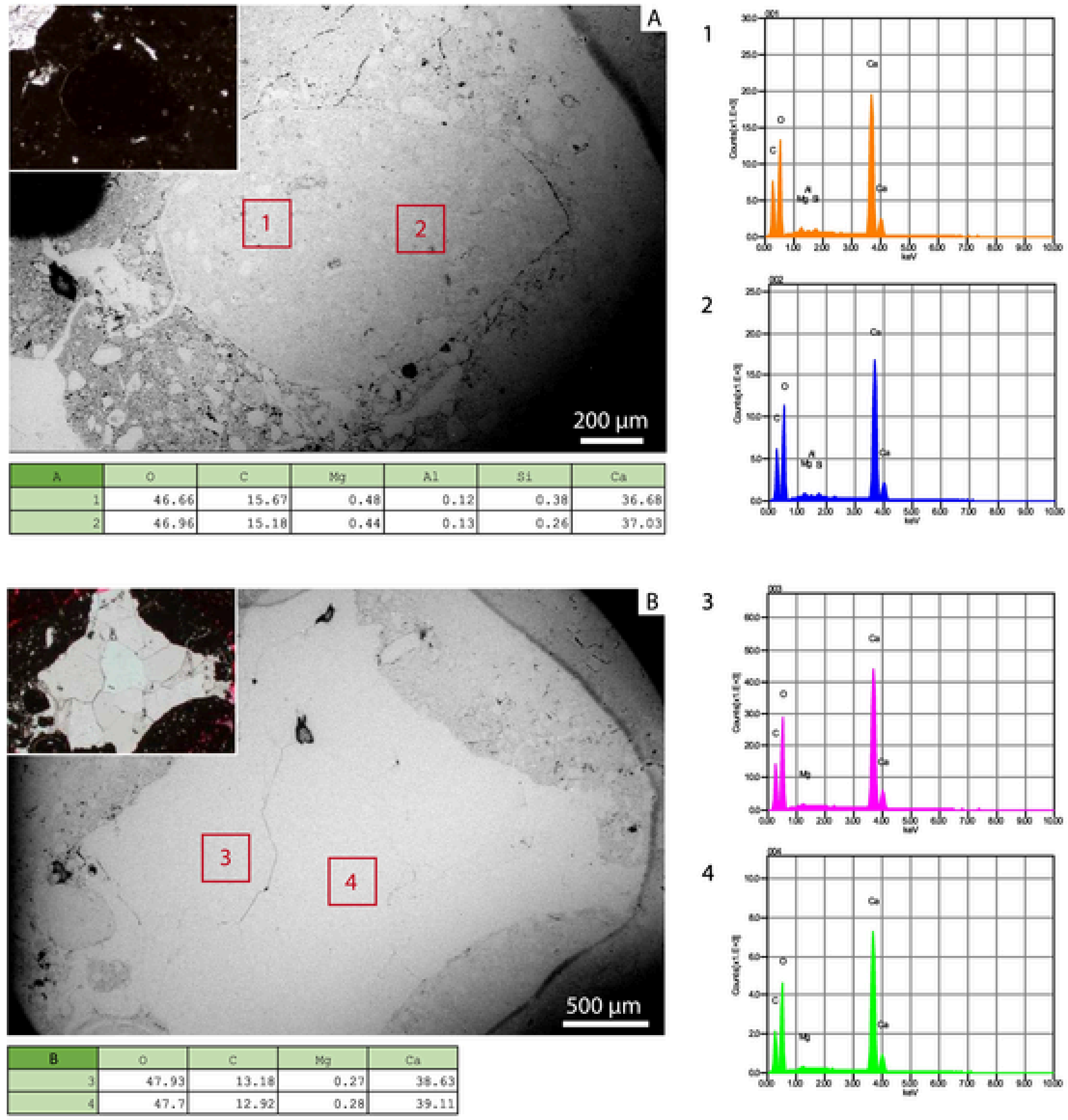
Curved fissures which commonly appear in all three subfacies from F3 are closely related to generation of intraclasts and nodules (Freytet and Plaziat, 1982; Martín-Chivelet and Giménez, 1992; Alonso-Zarza and Wright, 2010). These characteristic fissures, called circumgranular cracks (Fig. 7H), result from differential desiccation of grains and matrix (Freytet and Plaziat, 1982). Circumgranular voids are associated with planar and irregular void morphologies and are commonly filled by LMC blocky cement or microsparite.

Extreme development and evolution of fenestral porosity can lead to the in-situ formation of peloidal accumulations, a process known as grainification (Mazzullo and Birdwell, 1989; Wright, 1990). This process results in the peloidal packstone to grainstone textures from F4 (Fig. 8C–D–F). In some samples, peloids appear associated with prismatic and/or pyramidal carbonate particles of ~100 μm size interpreted as reworked grains of *Microcodium* (Fig. 8E). Pisoids, usually displaying only one coated layer are also a common component of this facies (Fig. 8F).

Pseudomicrokarst refers to irregular and complex cavities that resemble small-scale karst dissolution features in carbonate rocks (Plaziat and Freytet, 1978). The term “pseudo” connotes that these cavities formed by mechanical processes (mostly root bioturbation in soft sediment and subsequent desiccation), not through rock dissolution as in a karst system. However, the existence, in some cases, of rounded boundaries indicates that a minor dissolution took place (Platt, 1989). The most probable origin of the system of microcavities is sub-vertical root traces that became connected by horizontal fractures mostly generated by desiccation processes (Alonso-Zarza and Wright, 2010). The significant development of this feature in the studied sections supports root activity in the carbonates of Fortanete.

Pisoids are a common grain filling pseudomicrokarst cavities. Their coating genesis is controversial and has been related to different processes in vadose settings. Replacement processes are commonly associated with these coating features (clay replaced by micrite; Alonso-Zarza and Wright, 2010), however, the absence of quartz and non-carbonate grains inside the envelopes, along with many evidence of transport (filling porosity) almost discards this possibility. One of the most common processes for the formation of the coating is biogenic related to activity by algae or fungi in vadose settings (Wright, 1986; Jones, 1987; Alonso-Zarza et al., 1992). Furthermore, desiccation processes along with later rise of the water level in wetter periods, may cause the movement of grains over the sediment surface giving rise to coated micritic grains that are transported and end filling porosity of nearby areas (Alonso-Zarza and Wright, 2010).

Finally, *Microcodium* has mostly been found in facies F5 as reworked fragmentary aggregates (Fig. 8E) and individual grains making nuclei of micritic pisoids. Well-preserved *Microcodium* aggregates (Fig. 9D, F), composed of several grains, can be found in vugs infilled with peloids and blocky LMC cement. However, they are mostly found as isolated grains in micrite matrix. Despite its controversial origin (Freytet and Plaziat, 1982; Wright et al. 1995; Freytet et al., 1997; Kabanov et al., 2008), ancient *Microcodium* shares many attributes with modern intra-



A	O	C	Mg	Al	Si	Ca
1	46.66	15.67	0.48	0.12	0.38	36.68
2	46.96	15.18	0.44	0.13	0.26	37.03

B	O	C	Mg	Ca
3	47.93	13.18	0.27	38.63
4	47.7	12.92	0.28	39.11

Fig. 11. (A) SEM picture of a blackened nodule from the Fortanete Fm. (B) SEM picture of a pore filled by calcite blocky cement. Areas 1, 2, 3 and 4 went under a qualitative elemental analysis (EDS) and the results are shown in their respective tables and plots. Both pictures are taken from samples belonging to the Fortanete section (facies 3a).

cellularly calcified roots (Klappa, 1978; Jaillard et al., 1991; Košir, 2004). In-situ *Microcodium* structures normally exhibit corrosive contact with the substrate whereas disintegrated aggregates are often reworked as individual polyhedral elements and incorporated in calcretes and palustrine facies and also resedimented in marine sediments (Martín-Chivelet and Giménez, 1992; Košir, 2004). In palustrine facies of the Fortanete Fm, *Microcodium* structures have not been observed in situ but strongly fragmented and incorporated in clasts and matrix in multiple phases of sediment reworking.

5. The δ18O and δ13C data

The analysis of the isotopic composition (δ18O and δ13C) has proved to be an excellent palaeoenvironmental indicator in lacustrine carbonates (Teranes and McKenzie, 2001; Leng and y Marshall, 2004; Luzón et al., 2009, 2017). Regarding oxygen, the primary isotopic signal mainly depends on precipitation, evaporation, temperature, groundwaters, size/depth of the lacustrine system or residence time (Hoefs, 2009). On the other hand, carbon isotopic signal usually depends on the influence of organisms in the system, along with inorganic carbon (CO_2, HCO^{-3}). Evaporation and photosynthesis are the main processes leading to an increase of 13C in the water.

Vertical distribution of the obtained δ18O and δ13C data along the Fortanete log is shown in Fig. 12, whilst Fig. 13 shows the correlation between 13C and 18O. Results of C and O stable isotope composition of 23 bulk carbonate samples from the Fortanete section exhibit low variation of δ13C values (mean: −7.7 ‰, min: −8.8, max: −7.1), a relatively narrow range of δ18O values (mean: −4.7 ‰, min: −6.1 ‰, max: −3.8 ‰), and insignificant covariation between δ13C and δ18O (r = 0.04).

The Fortanete section values fit within the C and O isotope composition range of freshwater lake carbonates (Leng and y Marshall, 2004) and also correspond to isotope composition of palustrine carbonates, diagenetically modified by subaerial exposure (e.g. Platt, 1989).

In general, carbonates precipitated in open systems present low variability of δ18O values because the evaporation processes, which mainly controls δ18O variations, are less important than in closed big lake systems. Small lakes are more dependent on seasonality and tem-

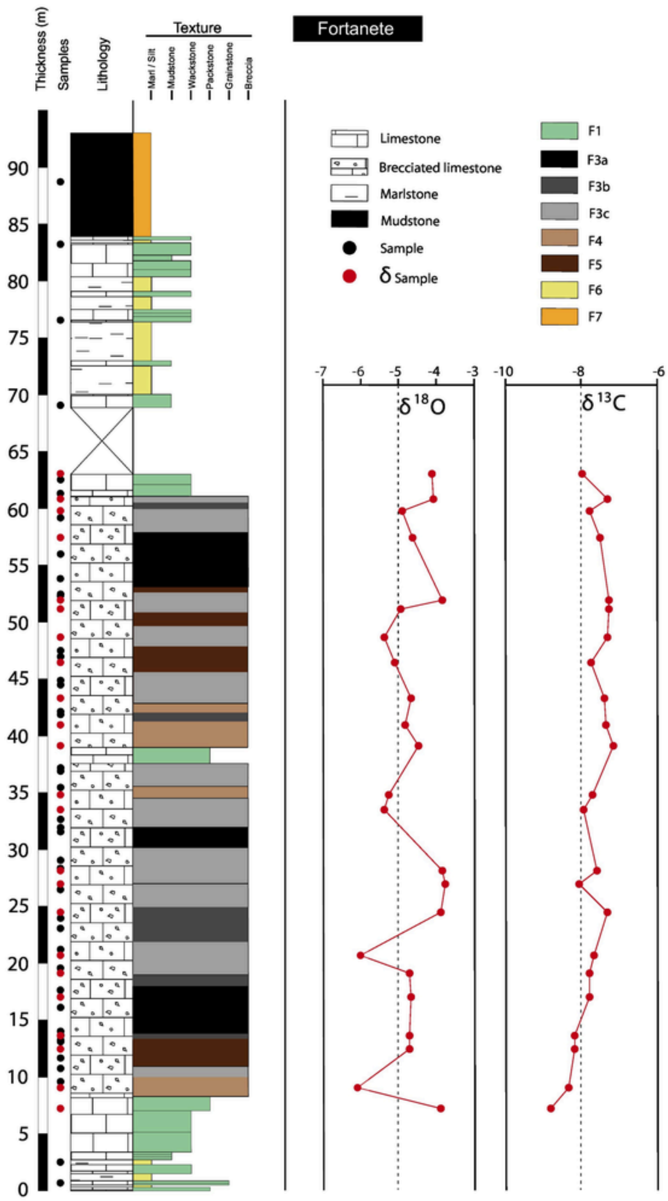


Fig. 12. Stratigraphic log from the Fortanete section, showing texture, thickness, lithology, facies and samples. The vertical evolution of samples used for the isotopic analysis is displayed for both ^{18}O and ^{13}C.

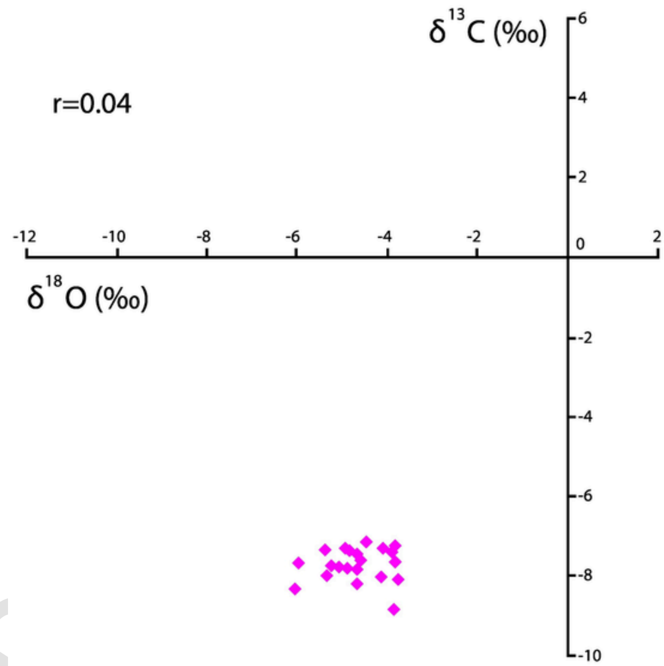


Fig. 13. δ^{18}O and δ^{13}C plot of the palustrine carbonates of the Fortanete Fm. The value of covariance (r) is indicated.

perature, whilst big lakes on precipitation and evaporation (Leng and Marshall, 2004). With short residence times water has less time suffering evaporation processes, so it is harder to expect big increments or abrupt changes in the δ^{18}O as what happens with the obtained data, with values ranging no more than 2 ‰.

Along with the low covariance, Talbot (1990) considers that this range of isotopic values belongs to small lakes with low wide/depth relations. However, low covariance and low variability of δ^{18}O values have been also related to groundwaters (Dunagan and Turner, 2004; Luzón, 2005; Luzón et al., 2017). Despite groundwaters and low evaporation being not incompatible theories, the sedimentary features described in this study seem to fit better with an open system with short residence times with low-evaporation impact, however, groundwater contribution should not be totally discarded. Lakes with low δ^{18}O variability, small size and short residence times have been described in literature, like the Lake Chuma in Kola Peninsula (Jones et al., 2004), Lake Abisko in Sweden (Shemesh et al., 2001), Hawes Water in UK (Marshall et al., 2002) or Lake Ammersee in Germany (von Grafenstein et al., 1999). Other palustrine systems in the Cretaceous of the Iberian Basin show similar isotopic values (Platt, 1989).

The marine influence and episodic transgressions in the area could have affected the isotopic values obtained in this study, mostly taking into account that samples were taken from the distal area of Fortanete. Seawater δ^{18}O and δ^{13}C values are usually significantly higher than those from continental waters (Leng and y Marshall, 2004), and are highly affected by temperature and global ice volume, being lower with high values of temperature (O'Neil et al., 1969).

It is well known that during Cretaceous green-house conditions dominated (Haq, 2014), resulting in low global sea δ^{18}O values (0–2 ‰). These are low values for sea water, but much higher that the isotopic values obtained for the Fortanete Fm. Palustrine carbonate δ^{18}O values normally are encompassed between −5 and −10 ‰ (Platt, 1989; Platt and Wright, 1992; Wright and Alonso-Zarza, 1992), however, slightly higher values (−5 to −6 ‰) are associated with marine influenced lakes (Tandon and Andrews, 2001), perfectly fitting with the values obtained in this study and thus strengthening the marine influence theory.

6. Palaeoenvironmental reconstruction

Heterogeneity of lithofacies distribution along the studied area is a key factor for the palaeoenvironmental reconstruction of the Fortanete Fm (Fig. 4). Analyses of lithofacies proportion in the different areas and the sedimentary features are the two main criteria for interpretation of subenvironments. As suggested by Platt and Wright (1992, 2023), palustrine carbonates should not only be considered to be related to shallow and low-gradient slope lakes, but to complex mosaics of subenvironments with lateral heterogeneity of facies. Studied data allowed differentiating three main subenvironments, each one of them dominated by characteristic lithofacies.

6.1. Marshes and shallow low-gradient slope lakes with stable water level

The central part of the study area is dominated by the lacustrine facies association (see "marl dominance" area in Fig. 4B). Charophytes mostly appear in freshwater even though they can tolerate certain levels of salinity (García and Chivas, 2004), and they can occur in depths within the photic zone down to 15–20 m (Cohen and Thouin, 1987). Many samples showed abundant preserved charophyte stems, that could be related to charophytes proliferating in low-energy and low-depth conditions since stems are generally not easily preserved (Dean and Fouch, 1983; Cohen and Thouin, 1987). The charophyte flora of the Fortanete Fm was unknown to date. Most of the samples show a poorly diverse assemblage composed of two species, belonging respectively to genera Sphaerochara and Strobilochara, with gyrogonites smaller than usual. Poorly diverse charophyte assemblages made of small gyrogonites are common in shallow ponds. These described features could be probably related to marshes with freshwater input and some isolated shallow low-gradient slope lakes. Wet conditions in this area were probably more intense than in the adjacent ones causing darker grey colours in marls and less desiccation features and pedogenic processes (Fig. 5). Furthermore, despite the relatively low size and diversity of charophytes, the high proportion of characean algae supports stable water body conditions over time (Vicente et al., 2016), that would also favour the decantation of marls (F6).

Our interpretation of shallow conditions in the water bodies indicated by analysis of charophyte diversity and quantity is supported by the absence of deep lake features. Deposits in big lakes lack evidence of in situ vegetation and bioturbation (Platt and Wright, 1991), whilst there is strong evidence of vegetation and bioturbation widely spread along all the facies from the Fortanete Fm. Additionally, this absence of bioturbation in deep lakes results in deposition and preservation of alternating lamination of organic and carbonate rich laminae (Kelts and Hsü, 1978; Cohen, 1989), features that are not recorded in this study.

Another evidence of a low-energy setting is the lack of grain-supported textures. Their absence reflects a lower wave energy and weak tidal action in shallow bodies of water (Platt and Wright, 1991). The main grain-supported textures found in the Fortanete Fm are those from facies F2 with large fragments of gastropods, most of them probably of *Lychnus*, also common in F3 and F4. The genus *Lychnus* is related to marshy areas where they live next to larger bodies of water (Freytet and Plaziat, 1982), and its accumulation could be related to episodic high-energy events such as storms.

6.2. Ephemeral lakes, lake margins and prairies with marine influence

Palustrine carbonates are usually deposited in lakes with low-gradient slope and low energy margins (Freytet and Plaziat, 1982; Platt and Wright, 1991) and adjacent areas, whilst deep lakes do not usually present palustrine evidence (Platt and Wright, 1992). The palustrine facies association is dominant in the northwest (Bea, Fonfría and Segura de Baños) and the southeast (Aliaga and Fortanete) areas ("limestone dominance", Fig. 4B). Most of these facies show features that indicate periodic subaerial exposure and, pedogenic modification and reworking, so their origin could be related to margin low-gradient slope shallow lakes and/or ephemeral lakes with variability in the water level, where palustrine conditions dominate over lacustrine ones. The presence of *Microcodium* provides unambiguous evidence of subaerial exposure (Esteban and Klappa, 1983). The grade of development of palustrine features is moderately higher to the southeast, which is related to the time of exposure, the higher, the more development (Platt and Wright, 1992). The palustrine outcrops reach more extension than the one expected for deposits restrained to lake margins, a problem also observed by Platt and Wright (1992). These palustrine features are probably also related to low-gradient slope prairies adjacent to the lakes which are also affected by water level fluctuations and subaerial exposure.

Fenestral fabric is largely developed in facies F3 and F4 (Fig. 5). In fact, facies F4 is characterised by a process of peloid formation related to extreme development of fenestral porosity, considered one of the most common processes in environments with long periods of subaerial exposure (Shinn, 1983; Alonso-Zarza and Wright, 2010; Pratt, 2010). Total absence of lamination in peloidal deposits suggests low-energy systems, in concordance with low-depth lakes with no active margins (Freytet and Plaziat, 1982).

Palustrine conditions of periodic inundation and exposure favour the formation of nodules, often followed by their reworking (Freytet and Plaziat, 1979; Freytet, 1984; Alonso-Zarza and Wright, 2010). Pseudomicrokarst cavities (F5) are also present in this facies and are one of the most typical features found in palustrine facies (Alonso-Zarza and Wright, 2010).

On the other hand, brecciation processes are common in areas of periodical subaerial exposure such as lake margins (Braithwaite, 2005). The evolution of brecciation processes in palustrine margins such as the Fortanete Fm is shown in Fig. 14, based on interpretations from Freytet and Plaziat (1982) and Alonso-Zarza and Wright (2010). The least common stage in this area would be stage 1 (Fig. 14 stage 1), presenting a more stable water-level with proliferation of charophytes and decantation of marls (mostly favouring facies 1 and 6). Stage 2 (Fig. 14 stage 2) serves as a representation of the first phases of water-level fluctuation, leading to desiccation in the margins. These first processes will firstly cause the formation of breccias from F3, being F3a located in further areas rarely reached by water. Stage 3 (Fig. 14 stage 3) represents a phase where water-level keeps receding and F4 would appear. Finally, stage 4 (Fig. 14 stage 4) represents a period when water-level fluctuations have been constant over time, leading to hard reworking of the whole margin and developing complex structures such as pseudomicrokarst (F5). Breccia is found in multiple levels of a single massive m-thick layer, indicating that the succession was subaerially exposed during multiple events (Alonso-Zarza and Wright, 2010; Fig. 14 stage 4).

Facies F3 and F4 also contain abundant gastropods, but in these facies gastropods are usually well-preserved non-fragmented *Lychnus* shells. Freytet and Plaziat (1982) associated *Lychnus* with lake margins at the end of the Cretaceous.

This study shows local presence of foraminifera in facies F1. Main foraminifera found are discorbids (small rotaliids) and small miliolids. Occurrence of discorbids normally indicates brackish waters (Lidz and Rose, 1989), whilst small miliolids are usually related to shallow marine environments (Brasier, 1975) including restricted lagoons (Murray, 1991). Charophytes, in low proportion, are found in some samples along with foraminifera. Hence, the presence of foraminifera is probably related to brackish environments close to the sea and/or sea incursions flooding the palustrine/lacustrine areas. In the Fortanete section dasycladacean algae have been found in very low amounts. This group of calcareous algae is characteristic of shallow-marine environments and went through a diversity crisis during Late Cretaceous (Barattolo, 1991, 2002). However, dasycladaceans were common in relation to marine incursions in the late Santonian of the studied area (Torromé et al., 2022; Torromé and Schlagintweit, 2023). For example, the section of Cosa shows the lowest amount of characean algae, in concordance with a higher proportion of foraminifera probably related to a stronger marine influence in the area. The presence of marine biota in the more southern localities of Cosa, Aliaga and Fortanete (see Fig. 4B) is in concordance with the overall palaeogeography of the northeastern Iberian Basin at the end of the Santonian and beginning of Campanian (Fig. 1B; Torromé et al., 2022).

The marine influence only affected the diversity of salinity-intolerant organisms such as charophytes and the appearance of isolated foraminifera. This fossil association is normally attributed to vadose non-marine settings (Chafetz et al., 1985). Furthermore, the coexistence of vadose and phreatic evidence probably means alternation in the amount of water in the sediment, which is in concordance with the existence of small lakes with water-level variability.

All these characteristics suggest that palustrine features are mostly related to a subenvironment mainly located at the margins of small lakes with low-energy and low-gradient slope, to prairies next to the

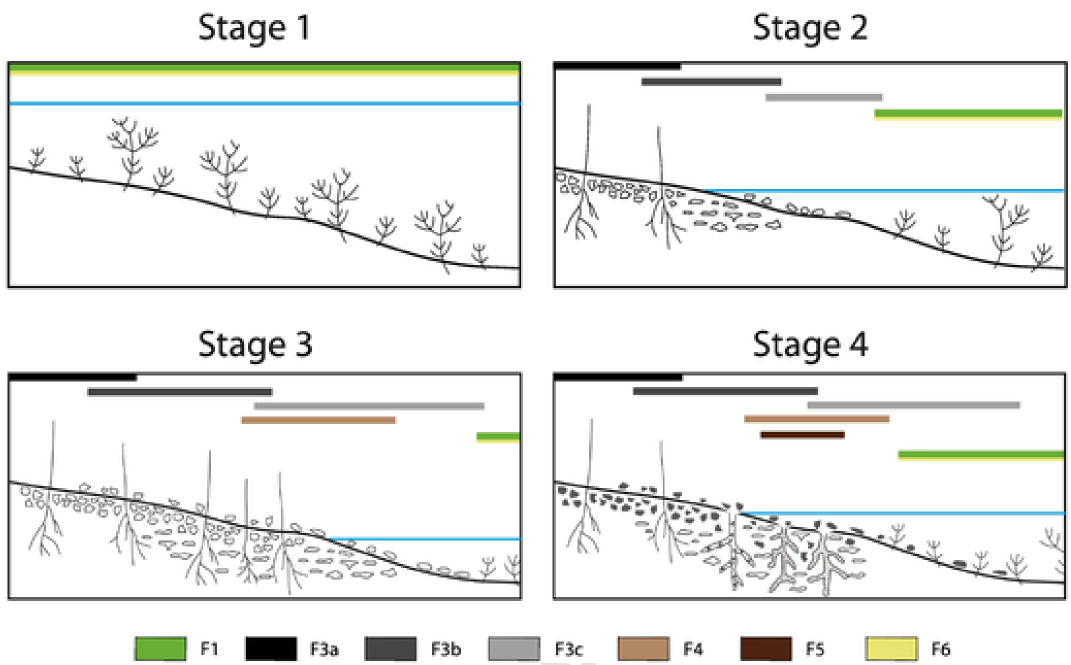


Fig. 14. Evolution of a lake margin in a palustrine setting (based on Freytet and Plaziat, 1982 and Alonso-Zarza and Wright, 2010). Stage 1: shallow water level with dominance of charophytes. Stage 2: drop of the water level led to desiccation, colonisation by plants and the beginning of brecciation processes. Stage 3: maintained drop of the water level over time leads to intense and complex brecciation and desiccation processes. Stage 4: the repetition of this fluctuation of the water level allows the formation of complex systems of pseudomicrokarst and palustrine features.

lake margins and to ephemeral lakes periodically desiccated, whilst marly-dominated deposits, that are still common, will still be associated with more stable water bodies that favour decantation and where only stage 1 (see Fig. 14) prevails. The distal localities of Fortanete, Aliaga and Cosa would have had marine influence.

6.3. Mudflats with saline and fine-siliciclastic input

This is the most marginal area of the studied sector, and is characterised as being the one with less carbonate content with predominance of the mudflat facies association. Palustrine carbonates are related to phases of subaerial exposure, so in more marginal areas with larger subaerial exposure impact, evaporite precipitation is expected (Platt and Wright, 1992). The northeastern localities of Degollados and Cuevas de Cañart ("mudstones and gypsum" dominance, Fig. 4B) include significant proportion of gypsum (F8). As in the other localities, charophytes still present low-diversity of species, whilst gyrogonites are even found in the gypsum nodules. The occurrence of charophyte gyrogonites and gypsum has also been evidenced in the Purbeckian of England, the Eocene of France, and the Cretaceous of China (Burne et al., 1980). This relation could be a result of seasonally variations in the salinity of shallow-lakes in semi-arid climatic conditions (Burne et al., 1980).

The nodular gypsum beds were probably formed by displacive growth of gypsum in soft sediment after the deposition of the host material (marly-mudstones and mudstones from F7), and thus should be considered as early diagenetic facies (Murray, 1964). Nodular gypsum in shallow-lake systems is common (Warren, 2010) and well understood due to the numerous studies in recent analogues (Schreiber and Tabakh, 2000). One of the main processes controlling its formation is subaerial exposure leading to the exposure of soft sediments in the marginal areas of the lacustrine–palustrine systems with episodic dry conditions that allow processes of evaporation (Murray, 1964).

In this marginal area the input of seawater is limited, and therefore other probable sources of evaporites in the mudflat were superficial runoff or saline groundwaters. Previous work noticed an increment of evaporite formation from late Santonian until middle Campanian in the south Iberian basin, probably related to the erosion of the Upper Triassic (Keuper facies) evaporites in the area (Mas et al., 1982). Nevertheless, this specific topic needs further research to explain a more precise source and origin of the gypsum levels.

7. Discussion

7.1. The overall tectonic setting

In the south Iberian Basin, the transition from marine and coastal environments with carbonate precipitation to continental environments with high detrital input is poorly known (García et al., 2004). Martín-Chivelet et al. (2019) helped in the understanding of the factors affecting the evolution of the Iberian Basin at the end of the Cretaceous, specially suggesting tectonic compression episodes during the Campanian, that along with the Late Cretaceous eustatic fall (Haq, 2014), lead to the transition from coastal to continental systems. However, interpretations and studies from specific sectors such as the Maestrazgo domain were generic and scarce.

The La Cañadilla Fm, the underlying unit to the Fortanete Fm, is a marginal marine unit that shows constant thickness and facies distribution over the study area (Torromé et al., 2022). Nevertheless, the overlying Fortanete Fm shows moderate to high variation in thickness, from 45–100 m-thick in the Eastern areas to 20–30 m-thick in the western ones, indicating irregular subsidence rates that could be caused by syntectonic activity. This activity is also the probable cause of the heterogeneity of facies in the Fortanete Fm (see Fig. 4), which is in contrast to homogeneity in the underlying La Cañadilla Fm. The heterogeneous facies pattern during the early Campanian is not only registered in the Fortanete Fm, and contemporaneous units in the other domains of the Iberian Basin which show strong differences in lithology (García et al., 2004). Tectonics is known as one of the main factors affecting the lateral heterogeneity of sub-environments in a lacustrine–palustrine system, with examples such as the Calama Basin in Chile with fluvio-lacustrine, palustrine, evaporite and alluvial fan settings (May et al., 1999).

The tectonic activity coeval to the sedimentation of the Fortanete Fm can be related to the onset of the Africa–Iberia–Europe convergence starting at late Santonian times. This convergence also caused the definitive interruption of the marine connection between Tethys and Atlantic oceans. After this convergence, all environments in the South Iberian Basin registered a major tectonic episode modifying the subsidence patterns and thus changing the palaeogeography and sedimentation (Martín-Chivelet et al., 2002). Landwards areas commonly suffered a decrease in the subsidence, whilst the distal marine domains increased their subsidence rates (Martín-Chivelet, 1996; Martin-Chivelet and Chacón, 2007). In the Fortanete Fm, the most distal areas with marine influence exhibit the highest thickness, probably associated with these major subsidence rates. Other possible explanations could be generation of higher accommodation space due to local tectonics or distribution of the main siliciclastic input. These last two theories could be related to the locality of Cuevas de Cañart, which is the only landwards locality presenting exceptional thickness. These kinds of exceptions were also registered in more areas of the Iberian Basin (Martín-Chivelet, 1995), which mentioned local tectonics as the most likely explanation.

In the landwards northwestern localities of the studied area, the beginning of the uplift of the Montalbán anticline (Fig. 3) probably led to a much lower accommodation space in the area, resulting in lower thickness. The major uplift processes giving rise to the Iberian Range mostly occurred during Eocene–Early Miocene (Casas et al., 2000; Capote et al., 2002; Antolín-Tomás et al., 2007), but these uplift processes started during the Campanian (Martín-Chivelet et al., 2019; Aurell et al., 2022). The change from extensional to compressional tectonics favoured the transition from shallow-carbonate platforms to coastal and continental environments, leading to subaerial exposure of vast areas (Martín-Chivelet, 1995, 1996). The coastal-lake environments that took over presented regional variation due to local factors, which could serve as a possible explanation of the strong facies variation that has been recognised in other Iberian systems such as the Rupelo Fm (Platt, 1989) or in the Madrid Basin (Alonso-Zarza et al., 1992).

7.2. Hydrological and climatic conditions

Extreme conditions of aridity or humidity are usually not favourable for the formation of carbonate in lakes (Cecil, 1990), being sub-humid alternating climates more appropriate (Platt and Wright, 1991; Sanz et al., 1995; Gierlowski-Kordesch, 1998). The studied features in the Fortanete Fm indicate fluctuating humid to slightly semi-arid climates along the basin. Gypsum deposits in the more marginal areas indicate that evaporation was higher than precipitation so the vadose/phreatic waters were concentrated and reached the saturation with respect to gypsum. This is coherent with the low preservation of organic matter in the associated mudstones and marly deposits (Dunagan and Turner, 2004). Tandon and Andrews (2001) proposed that pseudomicrokarst development should be higher in humid subtropical settings where the vegetation plays a bigger role than in semi-arid climates with herbaceous vegetation. However, this feature is also commonly found in sub-humid to arid (Dunagan and Turner, 2004) and semi-arid climates (Alonso-Zarza, 2003), which are likely to be more similar cases to the Fortanete Fm.

Additionally, the absence of evaporites and occurrence of darker marls rich in organic matter in the middle and western studied areas could mean a progressive increase in the water content to the west, along with reducing conditions and less concentration of salts. In addition, lower values of $\delta^{18}O$ are associated with humid conditions, whilst the higher the value, the more arid the climate (Leng and y Marshall, 2004). Isotopic values obtained in the present study are negative but close to 0 ‰, which along with multiple subaerial-exposure evidence and even local evaporites, could mean that there were not permanent conditions of humidity, but some seasonality to sub-humid slightly-drier conditions could be expected.

Similar climatic conditions can be observed in modern analogues such as the Florida Everglades, which present sub-humid but strongly seasonal climate conditions (Platt and Wright, 1992). Seasonality favours the exposure of the sediment. This allows developing soils on exposed sediments, being the sedimentary features of the Fortanete Fm (well-developed pseudomicrokarst, root traces and black pebbles) associated with intermediate to sub-humid climatic conditions (Platt and Wright, 1992), which also fits with the isotopic data of this study. A predominant sub-humid to intermediate climate would have intercalated with semi-arid episodes, leading to fluctuations in the water level and the development of pedogenetic processes. Precipitation of evaporites is likely associated with these fluctuating episodes, combined to larger underwater and/or runoff saline influx in the northeastern areas.

The most distal localities of Cosa, Aliaga and Fortanete were assigned to marginal marine areas around the Santonian–Campanian transition (Torromé et al., 2022). This fits well with them being the localities that register the episodic marine influence. Successive marine flooding events over marginal areas of the basin left an excellent sequential architecture preserved in the underlying La Cañadilla Fm (Torromé et al., 2022) and Sierra de Utiel Fm (Martín-Chivelet and Giménez, 1992). However, no cyclicity is recorded in the overlying Fortanete Fm. So, the common factors developing m-scale sequences in lacustrine–palustrine formations (i.e. periodical flooding-events, oscillating climate and/or short-term subsidence episodes: Huerta and Armenteros, 2005; Armenteros and Huerta, 2006) are not preserved in the massive breccia of the Fortanete Fm.

Despite marls being present in Cosa, Aliaga and Fortanete, limestones with palustrine evidence are by far more common, so low-energy lakes with palustrine areas would still dominate in this part of the region. Big saline lakes can have presence of both rotaliids and miliolids (e.g. Kawagata et al., 2005), but there is still no evidence of such big lake systems in the Fortanete palustrine-dominated system. Torromé et al. (2022) described a coastal facies belt with restricted ponds in this region by the middle Santonian–earliest Campanian, where charophytes and foraminifera were found together in brackish areas, which was not uncommon in the nearby coastal areas in the Mesozoic (Martín-Closas, 1989; Mojon, 2002; Sanjuan et al., 2021). The general regressive trend in the region (Alonso et al., 1993; Segura et al., 2004) would have induced a shift from these coastal areas to freshwater lakes, temporary ponds and marshes, sometimes still affected by minor marine input as suggested by $\delta^{18}O$ data (Tandon and Andrews, 2001) and marine skeletal grains. This kind of evolution has been recorded worldwide: in south America (Do Carmo et al., 2013; Antonietto et al., 2012; Tomé et al., 2014; Trabelsi et al., 2015), the West African margin (Grekoff and Krömmelbein, 1967; Krömmelbein, 1968; Colin and Jacobs, 1990; Colin and Dépêche, 1997), and North Africa (Andreu et al., 2003; Mojon et al., 2009). Reverse conditions (transgressive) in both marine and freshwater systems have also been analysed in the Sian Ka'an Wetlands of the eastern Yucatán Peninsula. This system, with an extension of 4000 km^2 is a low-relief complex of groundwater-fed freshwater marsh, lake and brackish coastal lagoons, showing also this combination of palustrine and marine features, but in this case the marine influence is higher (Platt and Wright, 2023).

7.3. Comparison to past and modern analogues

Palustrine carbonates in the geological record have been traditionally associated with shallow perennial lake margins (Freytet and Plaziat, 1982). However, Platt and Wright (1992) noticed that the origin of palustrine features should be more complex, not only because of the variety of environments in which palustrine rocks are found, but also due to the vast extension that these rocks can cover, something not possible for deposits that are limited to such a constrained area as lake margins. Despite it being correct that immediately adjacent areas to lake margins are more susceptible of suffering desiccation processes, the general low-gradient slope of these systems allows huge prairies and plain extensions next to the lakes to be also affected by water level variations. Palustrine deposits are thus more related to very shallow carbonate marshes rather than to only lake margins (Platt and Wright, 1992).

Similar marine-influenced palustrine deposits have been described in the Upper Cretaceous in the Coniacian–Early Campanian Sierra de Utiel Fm (Martín-Chivelet and Giménez, 1992). This unit was deposited south to the Iberian Basin, in the Prebetic domain. This marginal marine system was controlled by alternating events of marine flooding and freshwater influence involving strong pedogenetic processes, leading to the formation of palaeosols with pseudomicrokarst, nodules, black pebbles, desiccation features and charophytes. Another past analogue is found in the Bembridge Limestones from the Late Eocene of southern England. This geologic formation also displays complex pedogenetic processes forming brecciated and peloidal limestones over lacustrine deposits in freshwater to brackish settings with marine influence (Armenteros and Daley, 1998).

Analysing all the processes and features involving palustrine environments in the geological record is of vital importance to understand the factors controlling these systems, but it also requires an integrated approach. The identification of a clear modern analogue is necessary to complete the knowledge about these systems (Alonso-Zarza and Wright, 2010). Two of the main modern analogues referred in the literature are Las Tablas de Daimiel in Spain (Alonso-Zarza et al., 2006) and the Florida Everglades (Platt and Wright, 1992).

Las Tablas de Daimiel is one of the few freshwater wetlands areas that is still preserved in southern Europe. A drill hole study allowed the differentiation of three stages of evolution: a saline wetland developed under arid climate; an extensive peat developed during wet conditions; and finally palustrine carbonates affected by desiccation events (Alonso-Zarza et al., 2006). These different stages present similar features to those found in the Fortanete Fm. Drier conditions and evaporation leading to precipitation of evaporites could be compared to what is found in the mudflats, whilst the next stages show more resemblance to typical palustrine carbonates affected by desiccation and vegetation. However, Las Tablas de Daimiel is highly controlled by river activity (Alonso-Zarza et al., 2006). Lake margin reworking was probably much faster in Las Tablas de Daimiel due to fluvial connectivity between ponds and lakes.

In contrast, the Florida Everglades serves as a better analogue for the Fortanete Fm. This modern analogue allowed the re-interpretation of palustrine limestones to be not only related to shallow lake margins, but to shallow carbonate extensive wetlands (Platt and Wright, 1992). Furthermore, the Florida Everglades shows lateral heterogeneity of facies and subenvironments, presenting even brackish lagoons to the west of Miami due to the marine influence. This marine influence leads to the proliferation of dasycladacean algae in some of the Everglades lake systems, as it happens in the southeastern areas of Fortanete.

The everglades are also characterised by large areas with dense vegetation (marshes and swamps) and lakes forming areas of perennial algal carbonate sedimentation that coexist with desiccated and vegetated areas with subaerial exposure features. Absence of deep lake features and the general low-gradient slope in the system are other common points with the Fortanete Fm. Bigger lakes in the Florida everglades are also colonised by pulmonated gastropods (Platt and Wright, 1992), as it happens with *Lychnus* in the studied formation. In addition to this continental gastropod, non-skeletal black pebbles are also common in the everglades, mainly related to fires (Shinn and Lidz, 1987). Therefore, the Florida Everglades can be considered as an analogue of the Fortanete Fm since it presents similar conditions, features and distribution of subenvironments.

Although most palustrine units are associated with non-marine freshwater environments (Freytet and Plaziat, 1982), other units show heterogeneous associations of facies with marginal marine, brackish and freshwater facies and faunas (e.g. Eocene–Oligocene of southern England: Paul, 1989; Ramshaw, 1991). So, a complex distribution of subenvironments is common for palustrine carbonates both in the geological record and in modern systems. The Everglades is a vast densely-vegetated freshwater carbonate marsh, and lakes only cover a small portion of the area, a similar model to that proposed for the Fortanete Fm.

The Fortanete Fm is thus another analogue supporting that palustrine carbonates should be interpreted as complex mosaics of freshwater (sometimes marine influenced) environments rather than only as shallow low-gradient slope lakes. However, the numerous examples registered in the geological record and the huge variety of conditions in which a palustrine environment can be developed, require more research about this topic, and the study of more recent analogues.

8. Conclusions

The Fortanete Fm, deposited during Early Campanian in the northeastern areas of the South Iberian Ramp, has been characterised as a low-gradient slope wetland carbonate palustrine system consisting of marshes and shallow ephemeral lakes. Outcrops of the Fortanete Fm are subdivided into three main areas, each of them dominated by different lithofacies, interpreted as deposits of: (1) marshes and shallow low-gradient slope lakes; (2) ephemeral lakes, lake margins and prairies with variable water level and intermittent marine influence; an d (3) mudflats with input of saline waters and fine-siliciclastics.

The sedimentary features studied in the present work allowed explaining the processes acting over the system. Typical palustrine features are dominant in the southeastern and northwestern areas. Common features are pseudomicrokarst, brecciation, black pebbles, desiccation cracks, nodules, *Microcodium* fenestral fabric, root bioturbation, grainification and peloidal fillings. Palustrine elements are less frequent in the middle and northeastern areas, where marls rich in charophytes and mudstone with gypsum dominate respectively. Furthermore, despite palustrine systems being typically freshwater continental environments, marine influence in the Fortanete Fm is evidenced by the local presence of foraminifera and dasycladacean algae in the most distal localities of Fortanete, Cosa and Aliaga, located close to the coastal marine domain.

The isotopic data combined with all the sedimentary observations indicate that the most probable climatic conditions for the system were sub-humid with moderate seasonality to slightly drier conditions. The described data also allowed defining the subenvironment as a system of shallow lakes with low residence time, favouring episodic fluctuations of the water level.

The Florida everglades serve as a modern analogue of the Fortanete Fm, presenting also a complex distribution of subenvironments, low-gradient slope lakes and marine influence. The Fortanete case study also supports the model proposed by Platt and Wright (1992) of palustrine systems being related to wider areas and not only constricted to lake margins.

Uncited references

Declaration of competing interest

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

Data availability

Data will be made available on request.

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