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# SEDIMENTOLOGY AND PALEONTOLOGY OF THE LOWER MEMBER OF THE NOGUERAS FM (LOWER DEVONIAN) AT SANTA CRUZ DE NOGUERAS (TERUEL, NE SPAIN)

*Análisis sedimentológico y paleontológico del miembro inferior de la Fm. Nogueras (Devónico Inferior) en Santa Cruz de Nogueras (provincia de Teruel, NE de España)*

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**Abstract:** *An integrated sedimentological and paleontological analysis has been carried out in the lower member (d2a) of the shallow-marine Nogueras Formation (Lower Devonian, Iberian Chains). This formation represents the first carbonate-dominated and fossil-rich sedimentary unit of the Devonian of the Iberian Chains. Nine sedimentary facies, including terrigenous-clastic, mixed and carbonate facies, which are complexly intercalated at bed scale, have been characterized. Based on their sedimentary features and their lateral relationships using Markov chain analysis, two sedimentary models for the lower and upper part of d2a member have been proposed, which represent deposition in a mixed clastic-carbonate shallow marine depositional system. They include terrigenous-clastic intertidal deposits and predominant skeletal, carbonate-dominated and grain-supported facies in the high-energy shallow subtidal zone, whith a clear zonation of the skeletal components (brachiopods, bryozoans and crinoids, from shallow to relatively deep areas). Phosphate nodules, phosphatized fossils, ferruginous crusts and iron ooids, which are frequently associated with the relatively shallower bioclastic brachiopod facies, were probably linked to mineral continental sources and to remobilization in the shallow water high-energy area. The paleontological analysis shows that some of those organisms lived in protected areas of the subtidal zone, including in particular high-diversity communities of brachiopods, adapted to turbid waters with fine terrigenous suspended sediments.*

**Keywords:** *Lower Devonian, mixed clastic-carbonate platform, brachiopods, Iberian Chains, Santa Cruz de Nogueras, Teruel.*

**Resumen:** *Se ha realizado un análisis sedimentológico y paleontológico integrado del miembro inferior (d2a) de la Formación Nogueras, que representa la primera unidad marina somera predominantemente carbonatada del Devónico de las Cadenas Ibéricas. Se han definido nueve facies sedimentarias terrígeno-clásticas, mixtas y carbonatadas, que están complejamente intercaladas a escala de capa, depositadas en un sistema mixto detrítico-carbonatado de aguas someras. En función de sus rasgos sedimentarios y del análisis de sus relaciones laterales mediante cadenas de Markov, se proponen dos modelos sedimentarios para la parte inferior y superior del miembro estudiado. Los dos modelos incluyen depósitos terrígenos en la zona intermareal y facies carbonatadas bioclásticas en la zona submareal somera, con una clara zonación de sus componentes esqueléticos dominantes (braquiópodos, briozoos, crinoides, desde la zona somera a la relativamente profunda). Los nódulos de fosfato, fósiles fosfatizados, costras y ooides ferruginosas frecuentes en las facies bioclasticas de braquiópodos relativamente someras, se relacionaron probablemente con aportes minerales desde el continente y retrabajamiento en la zona marina de alta energía. El análisis paleontológico muestra que algunos de estos organismos vivían en áreas protegidas de la zona submareal, incluyendo particularmente comunidades con alta diversidad de braquiópodos, adaptadas a aguas turbias con elevado sedimento terrígeno fino en suspensión.*

**Palabras clave:** *Devónico Inferior, plataforma mixta terrigeno-carbonatada, braquiópodos, Cadenas Ibéricas, Santa Cruz de Nogueras, Teruel.*

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## Introduction

The shallow marine sedimentary successions of the Upper Silurian and Lower Devonian of the Iberian Chains (NE Spain) crop out with relative continuity in the Herrera Unit, in particular in the so-called *Depresión Axial del Río Cámaras* (DARC; Teruel province; Fig. 1A-C). The DARC represents a key area of the Iberian Chains to analyze and correlate the Lower and Middle Devonian stratigraphic successions of the Ibero-Armorican Arc domain (Carls, 1999). The sedimentation of the Lower Devonian successions of this area took place in a small intracratonic marine basin, the so-called Ibero-Armorican Trough (IAT), located between the emerged areas of the Cantabro-Ebroian Massif (CEM) and Central-Iberia (CI) in the margin of Gondwana at about 45º southern latitude (Carls, 1988; Cocks and Torsvik, 2002; Fig. 1D). Due to the general greenhouse conditions during the Early Devonian, the area was in a warm-temperate climatic belt (Fig. 1D) with low latitude sea surface water temperatures ranging between 30–32 °C (Lochkovian) to 22 °C (late Emsian; Joachimski *et al.*, 2009).

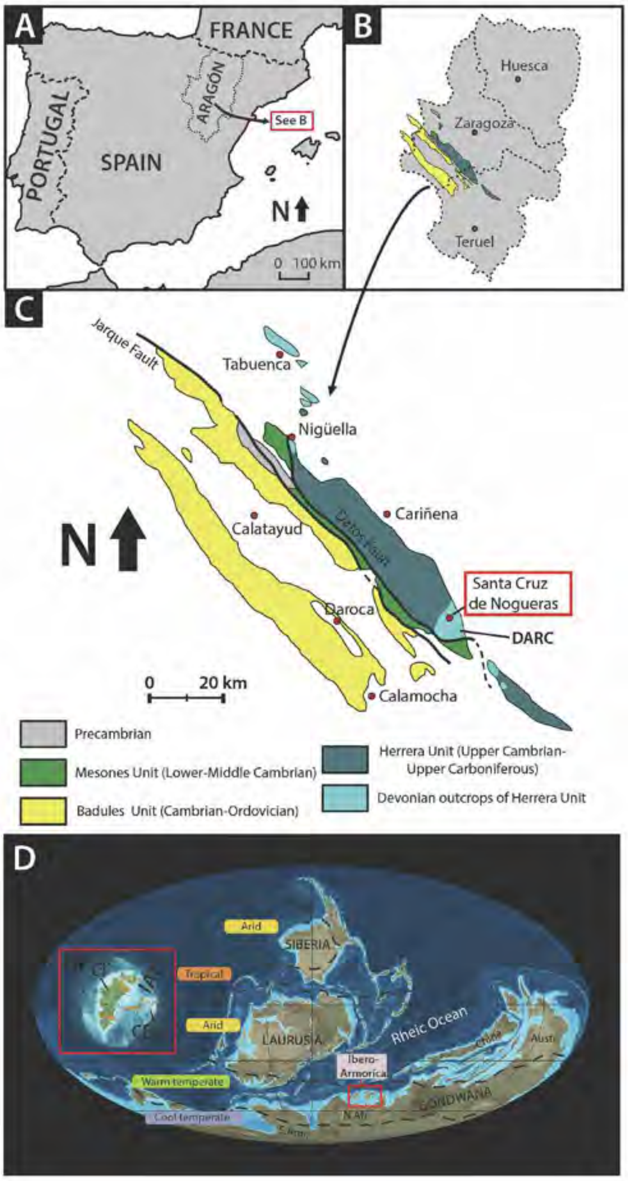

**Fig. 1.-** A, B. General geographic setting of the study area. C. Paleozoic outcrops of the Iberian Chains, indicating the location of the *Depresión Axial del Río Cámaras* (DARC) of the Herrera Unit (adapted from Gozalo and Liñan, 1988). D. Global palaeogeographic and paleoclimate reconstruction for the Early Devonian, and location of the Ibero-Armorican through (IAT; see insert), between the Cantabro-Ebroian Massif (CEM) and Central Iberia (CI). Arrows indicate detrital sources from the emerged areas. Adapted from data by Carls (1988,1999) on paleomaps by Blakey (2018) and Scotese (2018).

The Early Devonian succession within the DARC is characterized by a *ca.* 800 m-thick alternation of terrigenous clastic and carbonate deposits with abundant fossil remains (Fig. 2A). The predominance of carbonate- and fossil-rich sediments *vs.* terrigenous-clastic deposits has been related to variations in the terrigenous input from the CEM and CI, and the recorded carbonate-clastic sequences (*rythmothems*) has been interpreted as formed in tune with deepening-shallowing episodes (Carls, 1988, 1999). Within these successions, the *ca.* 140 m-thick Nogueras Fm (Lower Devonian: upper Lochkovian-lowermost Pragian; Carls and Gandl, 1967) represents the first carbonate-dominated and fossil-rich sedimentary unit of the Lower Devonian (Fig. 2A). This unit locates between the dominant terrigenous-clastic Luesma and Santa Cruz formations. The Nogueras Fm is characterized by an alternation of dm- to m-thick limestones and shales (mudstones) and occasional intercalations of sandstones and marls, with abundant fossil remains (mainly bryozoans, brachiopods, crinoids, trilobites, tentaculitids, cephalopods, conodonts and vertebrates). The unit has been divided in three members (d2a–d2c: Carls and Gandl, 1967), mainly based on the predominance of limestones in members d2a and d2c, and shales in the intermediate member 2db (Fig. 2A).

The Nogueras Fm was interpreted as shallow marine deposits accumulated at depths less than 60 m (Carls, 1988, 1999). Most of the previous studies on this shallow marine unit have been focused on the general sedimentary context and paleontology (Carls and Gandl, 1967; Carls, 1988; Carls and Valenzuela-Ríos, 2002), or in the analysis of specific fossil groups (*e.g.*, fish remains: Botella and Valenzuela-Ríos, 2002; Botella *et al.*, 2006, 2009, 2012; brachiopods: Carls, 1974, 1985; Carls and Valenzuela-Ríos, 1998; Carls *et al.*, 1993; Schemm-Gregory, 2011; ostracods: Dojen, 2005; Dojen *et al.*, 2004, 2007). However, to date, there is none integrated sedimentological and paleontological analysis that precisely defines the sedimentary model and the biotic assemblages recorded in the different shallow marine depositional subenvironments.

The main objective of the present work is the combined sedimentological and paleontological analysis of the carbonate-rich lower member of the Nogueras Fm (upper Lochkovian member d2a of Carls and Gandl, 1967; Fig. 2A) in the outcrops near the village of Santa Cruz de Nogueras, located within the DARC, which correspond to the type area of the unit. Member d2a has been selected for this study because: 1) it has a high variety of facies (carbonate, terrigenous-clastic and mixed facies), including the first fossil-rich carbonate deposits of the Devonian; 2) it crops out in stratigraphic continuity thus allowing a detailed bed-by-bed analysis and characterization of the main facies, fossil content and related depositional subenvironments. The overlying members d2b and d2c do not have the required conditions for a detailed bed-by-bed facies and paleontological analyses due to their homogeneous lithology (shale-dominated

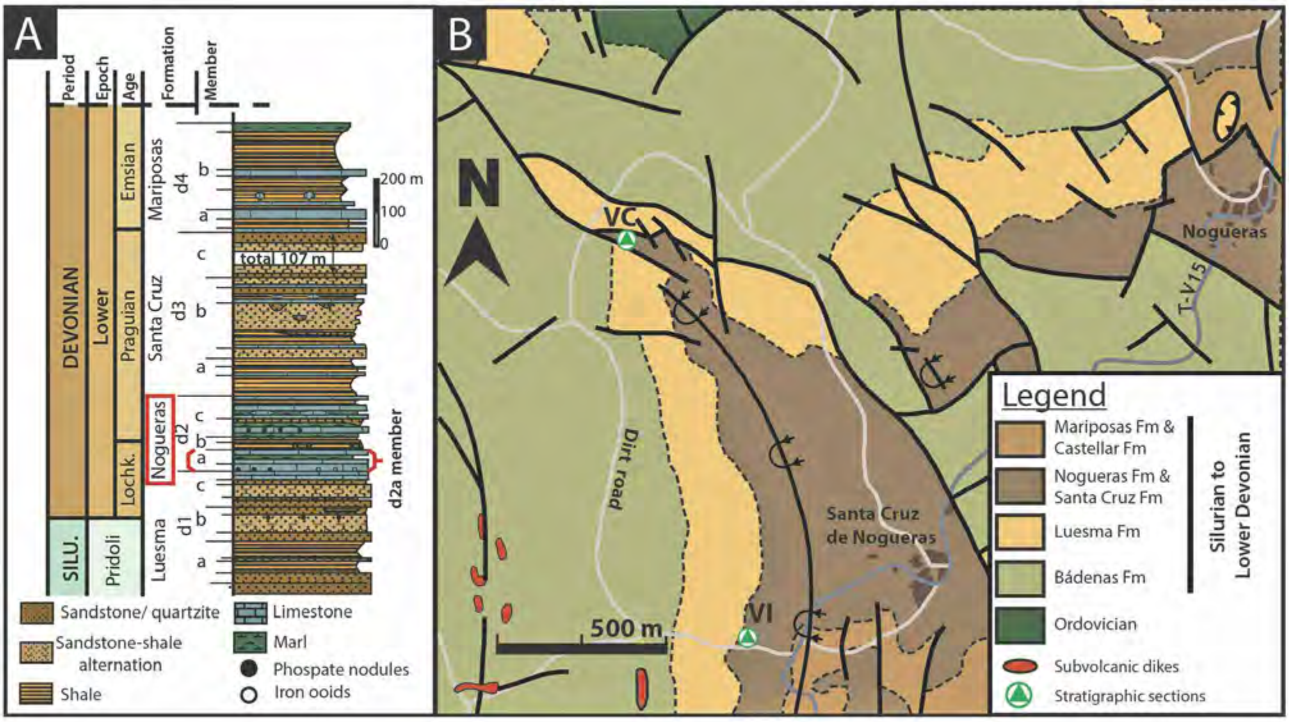

**Fig. 2.**- A. Synthetic stratigraphic log of the Lower Devonian of the Iberian Chains in the DARC (simplified from Carls and Valenzuela-Ríos, 2002). B. Geological map of the Santa Cruz de Nogueras area, with the location of the studied Las Viñas (VI) and Virgen del Carmen (VC) stratigraphic sections (adapted from Lendínez *et al.*, 1989).

member d2b) or to the tectonic complexity of the outcrops (member d2c). The obtained results of the combined sedimentological and paleontological analysis will allow characterizing the facies and main biotic assemblages within different shallow marine subenvironments, and to discuss the possible significance of the alternation of carbonate-rich *vs.* terrigenous-rich deposits (*i.e.*, clastic-carbonate sequences) in the context a mixed clastic-carbonate system.

## Geographic setting and methods

The outcrops of member d2a of the Nogueras Fm studied here are located in the surroundings of the village of Santa Cruz de Nogueras, in the northern part of the Teruel province, NE Spain (Fig. 2B). The d2a member is *ca.* 40 m in thickness and has been studied in two partial stratigraphic sections that have allowed characterizing the entire d2a member: *Las Viñas* section (VI) and *Virgen del Carmen* section (VC), located respectively to the SE and NW of Santa Cruz de Nogueras (Fig. 2B). In the studied area, the Silurian-Devonian rocks are structured in a large recumbent synclinal fold (Fig. 2B). The section VI locates in the southern part of the inverted limb (Figs. 2B and 3A), whereas section VC is placed in the northern part of the normal limb, near the hinge line in an abandoned galena mine and other iron-rich minerals of hydrothermal origin (Figs. 2B and 3B).

The stratigraphic and sedimentological analysis has been based on a bed-by-bed and sub-bed level scale field study of lithology, texture, components and sedimentary structures, which was complemented with the description of 31 rock samples in polished slabs and 11 selected thin sections of the main facies under petrographic microscope. However, the limited lateral extent of outcropping beds (Fig. 3) has prevented the accurate

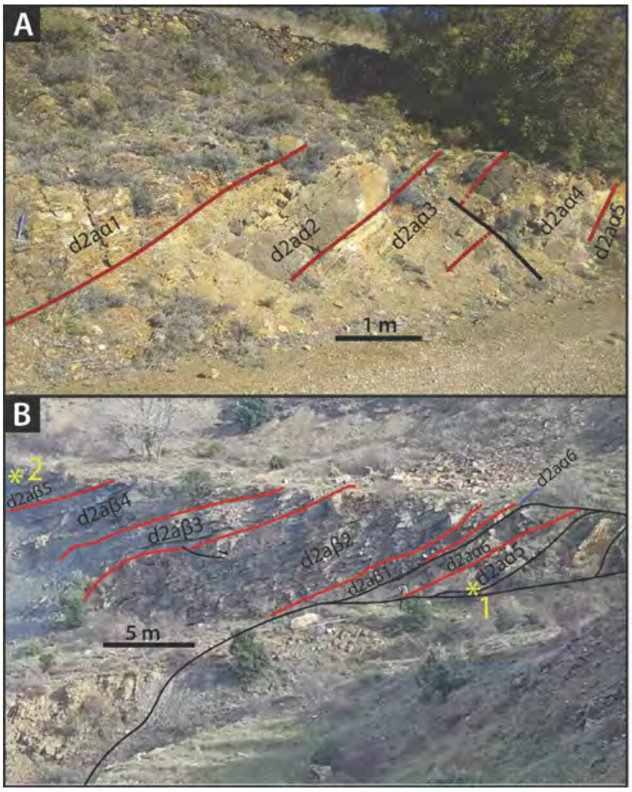

**Fig. 3.**- Field images of the lower member d2a of the Nogueras Fm in VI section (A) and VC section (B). The black lines point out faults and the red lines highlight the boundaries of the submembers defined by Carls and Gandl (1967): submember d2aα (including units 1 to 5) and submember d2aβ (including units 1 to 5). Notice the inverted bedding in VI (A) and the normal bedding in VC (B). In VC, the yellow stars indicate the bottom and the top of the stratigraphic section.

description of the lateral continuity of some sedimentary structures (*e.g.*, cross bedding and channelized bases). The purpose of this analysis has been the definition of several sedimentological facies and the study of their vertical and lateral relationships. To unravel the most probable lateral relationship of facies during deposition, the Markov Chain stochastic model following the method of Harms *et al.* (1982) has been applied to the observed vertical facies changes. This analysis consists on obtaining a matrix that evaluates the probability that one facies passes to another, thus deciphering the most frequent facies transitions.

A paleontological analysis has also been carried out by characterizing the skeletal debris in all beds and sampling entire fossils in 16 beds. The main fossil groups have been studied from a taxonomic, taphonomic and paleoecological point of view. In addition, a calcareous bed bearing a great accumulation of fossils has been analyzed in detail in a square grid of 25x25 cm. Taxonomic counting and taphonomic analyses have been performed in order to extrapolate the relative abundance of the main fossil groups and their preservation.

## Results

### *Stratigraphic and sedimentological analysis*

*Lithological succession*. Carls and Gandl (1967) identify two submembers and different units within the lower member d2a of the Nogueras Fm: submember d2aα (including units d2aα1 to d2aα5) and submember d2aβ (including units d2aβ1 to d2aβ5). In the studied VI and VC sections (Fig. 3) these lithostratigraphic units have been identified (d2aα1–most of d2aα5 in VI; upper part of d2aα5–d2aβ in VC) allowing the correlation between both sections and the characterization of the entire d2a member. Nevertheless, there is some uncertainty concerning the thickness of unit d2aα5 due to tectonic deformation and the impossibility of its physical tracing between both sections.

| FACIES | | MAIN GRAINS | ACCESORY GRAINS | BEDDING AND STRUCTURES |
|---|---|---|---|---|
| Terrigenous-clastic | **Mudstones (claystones/siltstones, C)** | Detrital mud | - | - Tabular cm- to dm-thick levels (30 cm in average)<br>- Parallel lamination |
| | **Sandstones (S)** | Detrital/calcareous mud<br>Well sorted fine quartz grains | Bioclasts (<15%) of brachiopods, crinoids and bryozoans (fragmented). Occasional vertebrates (conodonts and fish remains?) | - Tabular or slightly wavy levels (10 cm in average)<br>- Cross lamination, current and wave ripples and local bioturbation |
| Mixed | **Brachiopod marls (Bm)** | Entire brachiopods (20-30%), usually articulated | Entire bryozoans, orthocerids, tentaculitids, bivalves (10-15%) | - Irregular to tabular cm-thick levels (8 cm in average)<br>- Occasional bioturbation and intercalated limestone lenses |
| | **Sandy limestones (Sl)** | Poorly sorted fine to coarse quartz grains (50%) | - Bioclasts of brachiopods and bryozoans (30%) and crinoids (10%)<br>- Occasional phosphate nodules and intraclasts | -Tabular dm-thick levels (25 cm in average), locally with channelized bases (few cm-depth and few dm-long)<br>-Planar, trough and herringbone cross-bedding, occasional bioturbation and ferruginizations. |
| Carbonate | **Packstones/Grainstones of reworked brachiopod (P/G brr)** | Disarticulated valves and rounded bioclasts of brachiopods (0.05-2 cm in size) (65%) | - Bioclasts of bryozoans, crinoids, bivalves, ostracods, trilobites (15%) and locally,fish remains<br>- Iron ooids (5-10%)<br>-Occasional phosphate nodules (mm to cm in diameter) | - Tabular dm-thick levels (30 cm in average), locally with channelized bases (few cm-depth and few dm-long)<br>- Occasional planar cross-bedding, ferruginized levels and bioturbation |
| | **Packstones/Grainstones of *'in situ'* brachiopods (P/G bri)** | Entire brachiopods with articulated valves (0.5-5 cm in size) (80%) | - Entire bryozoans and tentaculitids, bioclasts of crinoids (10%) | Tabular cm- to dm-thick levels (10 cm in average) |
| | **Packstones/Grainstones of reworked bryozoans (P/G byr)** | Ferruginized, rounded and phosphatized bioclasts of branching and hemispherical bryozoans (0,5-8 cm) (50%) | - Disarticulated valves and bioclasts of brachiopods (20-25%), bioclasts of crinoids (10%), and locally fish remains. Occasionally phosphatized.<br>- Local reworked phosphate nodules (mm to cm in diameter) and iron ooids in vertebrate levels | - Tabular to irregular dm-thick levels (15 cm in average)<br>- Occasional planar cross-bedding and ferruginized crusts |
| | **Packstones/Grainstones of *'in situ'* bryozoans (P/G byi)** | Entire branching and hemispherical bryozoans, sometimes in life position (0,5-15 cm) (70%) | Disarticulated valves and bioclasts of brachiopods (15-20%), and bioclasts of crinoids (10%) | - Tabular cm-thick levels (9 cm in average)<br>- Bryozoans growing on ferruginous crusts on tops of strata of P/G byr facies |
| | **Packstones/Grainstones of crinoids (P/G c)** | Bioclasts of crinoids (ossicles, and stems fragments) (0,15-2 cm) (45%) | Disarticulated valves and bioclasts of brachiopods (25-30%), and bioclasts of bryozoans (15%), ostracods and locally, ortocherids<br>- Local phosphate nodules (mm to cm in diameter) and iron ooids | - Tabular dm- to m-thick levels (50 cm in average)<br>- Frequent parallel lamination with variation in grain size, and frequent ferruginous crusts<br>- Local paleokarst surface |

**Table 1.-** Main sedimentological features of the facies defined for the lower member d2a of the Nogueras Fm.

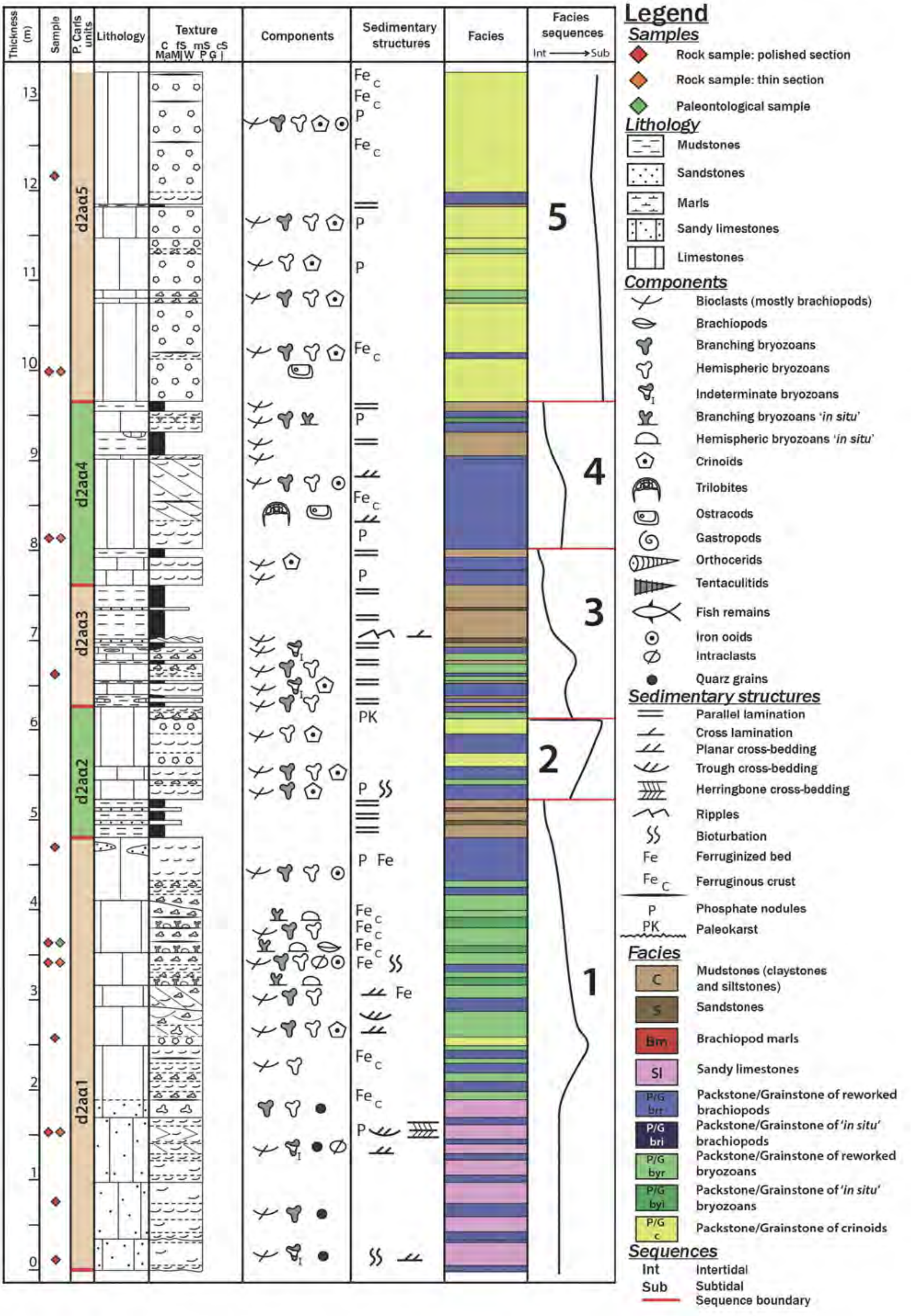

**Fig. 4.-** Las Viñas (VI) stratigraphic section of the lower d2a member of the Nogueras Fm. This section encompasses the submember d2aα, from d2aα1 unit to the most of d2aα5 unit, defined by Carls and Gandl (1967).

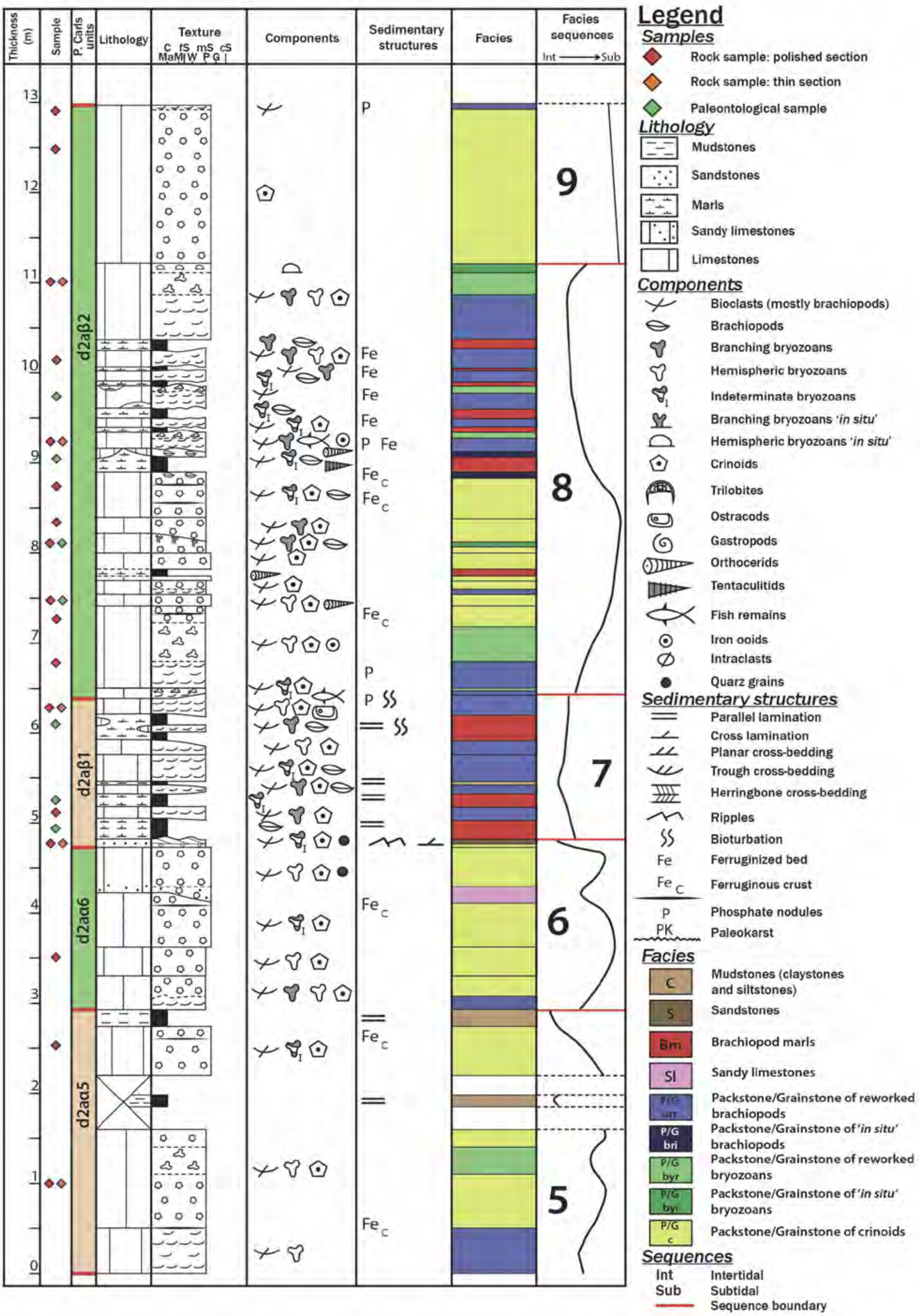

**Fig. 5.-** Virgen del Carmen (VC) stratigraphic section of the lower d2a member of the Nogueras Fm. This section encompasses the upper part of unit d2aα5 of the submember d2aα and the entire submember d2aβ, defined by Carls and Gandl (1967). See the upper part of the log in the next page.

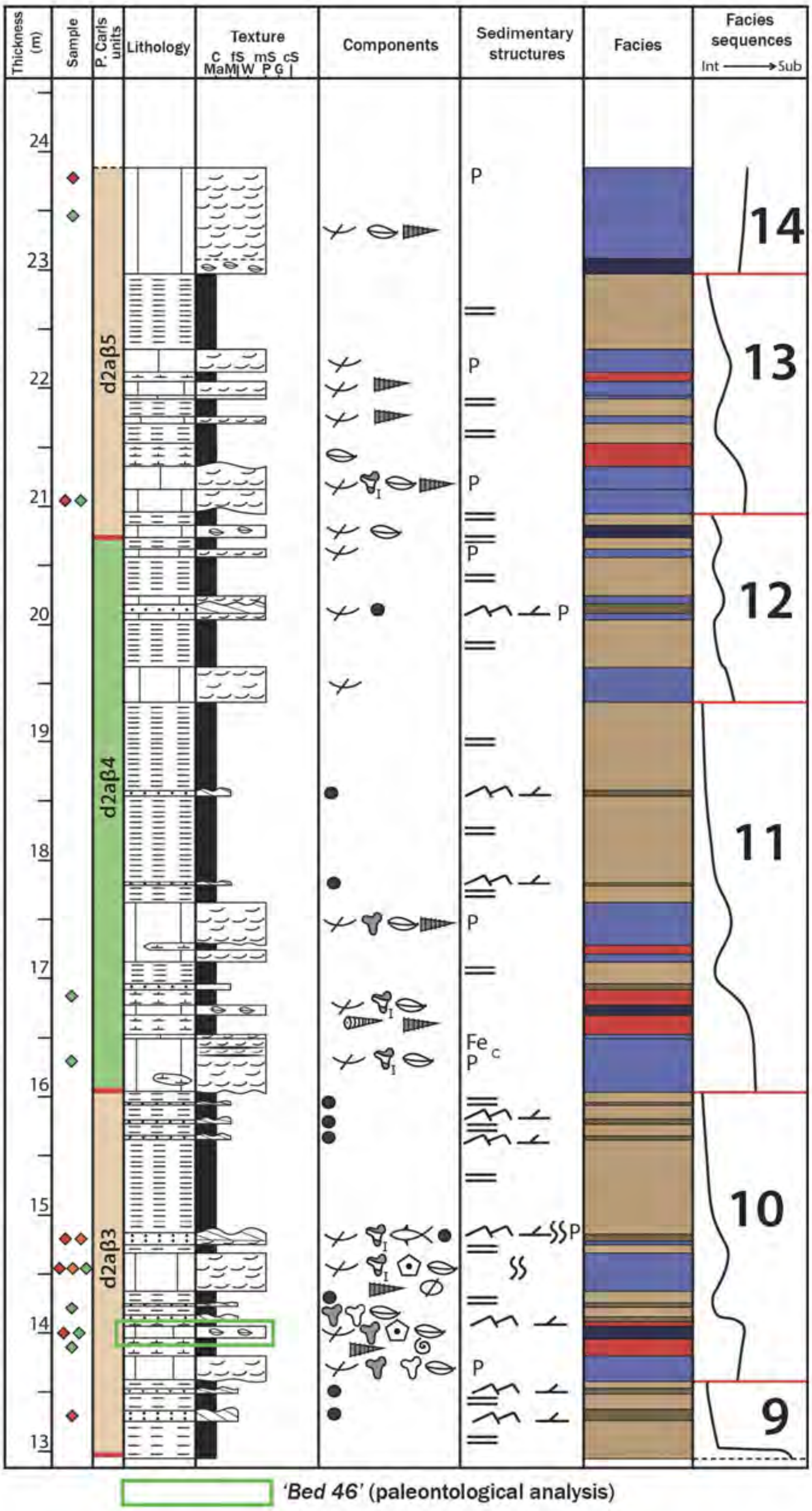

**Fig. 5.-** (Continued)

The section VI starts at the base of the Nogueras Fm, which is marked by the first fossiliferous limestones on top of the dominant terrigenous-clastic succession of the Luesma Fm. This section is *ca.* 13 m in thickness and includes almost the entire d2aα submember, from d2aα1 to most of d2aα5 (Figs. 3A and 4). The succession is characterized by sandy limestones and skeletal limestones (d2aα1) passing upwards to an alternation of mudstones, sandstones and skeletal limestones (d2aα2–d2aα4), and to crinoidal limestones (d2aα5). The section VC is *ca.* 24 m in thickness and encompasses the upper part of d2aα5 and the whole d2a submember (Figs. 3B and 5). This section includes in its lower part an alternation of skeletal limestones and fossil-rich marls (d2aα5 and d2aβ1–d2aβ2). Towards the top, in d2aβ3–d2aβ5, terrigenous-clastic lithologies (mudstones, sandstones) dominate, and phosphate nodules and vertebrate remains occur.

*Facies description*. Field analysis and petrographic study of rock samples in polished slabs and thin sections have allowed to characterize 9 facies, including terrigenous-clastic, mixed and carbonate facies, which are complexly intercalated at bed scale (Figs. 4 and 5). The detailed description of facies is included in Table 1 and the main sedimentary features are illustrated from field and sample images in figures 6 and 7.

Terrigenous-clastic facies encompass mudstones (mainly claystones; facies C) and sandstones (facies S). Facies C is arranged in cm- to dm-thick levels, has parallel lamination and is barren of fossils. Facies S corresponds to cm-thick bedded fine-grained sandstones with local current and wave ripples, and frequent parallel and cross lamination and bioclasts of brachiopods, crinoids and bryozoans (Fig. 6A, B).

Mixed facies include brachiopod marls (facies Bm) and sandy limestones (facies Sl). Facies Bm is arranged in cm-thick irregular beds and has abundant articulate brachiopod shells and minor proportion of bryozoans, tentaculitids and orthocerids. The sandy limestones (facies Sl) are arranged in dm-thick tabular levels, with occasional low relief channelized bases, and have planar-, trough- and herringbone cross-bedding characterized by sand-rich and skeletal-rich laminae with bioclasts of brachiopods, crinoids and bryozoans (Fig. 6C, D).

Carbonate facies correspond to skeletal limestones, with packstone/grainstone (P/G) texture. Based on the main skeletal components (brachiopods, bryozoans and crinoids) and taphonomic criteria (reworked fossil debris vs. *in situ* entire fossils), 5 carbonate facies have been differentiated

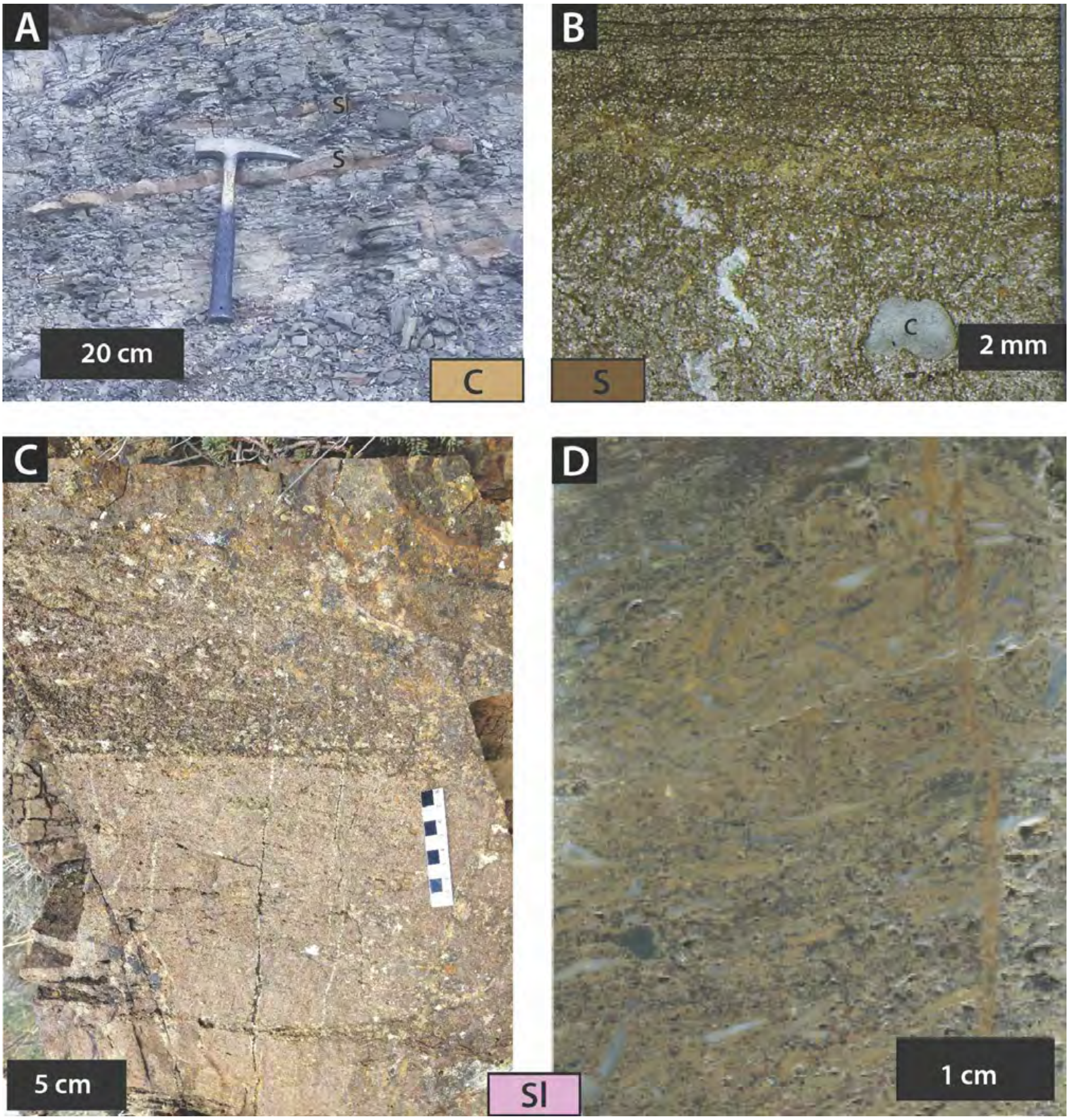

**Fig. 6.-** A. Field image of facies C (mudstones), with intercalated sandstone facies S (sandstones). B. Thin section image of facies S (c: crinoid). C. Field image of Sl facies (sandy limestones), with a herringbone cross-bedding. D. Polished section image of Sl facies.

(Table 1). The P/G of reworked brachiopods (facies P/G brr) is arranged in irregular levels up to 30 cm-thick, with local low-relief channelized bases and planar cross-bedding, and is characterized by abundant disarticulated valves and bioclasts of brachiopods, and minor proportion of bryozoans and crinoids (Fig. 7A, B). Iron ooids (with obscured nucleus and cortices due to complete ferruginization), ferruginous crusts on some bedding surfaces, and mm- to cm-sized phosphate nodules are also present. The P/G of *in situ* brachiopods (facies P/G bri) forms cm-thick tabular levels plenty of well-preserved articulate brachiopod shells. It also includes bioclasts of bryozoans and crinoids.

The P/G of reworked bryozoans (facies P/G byr) is arranged in cm-thick tabular levels with occasional tabular cross-bedding and occasional ferruginous crusts on top. The facies bears abundant bioclasts of bryozoans, and minor proportion of brachiopods and crinoids and iron ooids (Fig. 7C, D). The bryozoan debris are usually ferruginized, phosphatized and accumulated. Conversely, the P/G of *in situ* bryozoans (facies P/G byi) has well-preserved bryozoans in life position growing on ferruginous crust top surfaces of facies P/G byr, as well as debris of brachiopods and crinoids (Fig. 7E, F). Finally, the P/G of crinoids (facies P/G c) forms dm- to m-thick tabular levels and is mainly formed by crinoid ossicles and stem fragments and debris of brachiopods and bryozoans. This facies also show common parallel lamination and ferruginous crusts, and local iron ooids and phosphate nodules (Fig. 7G, H).

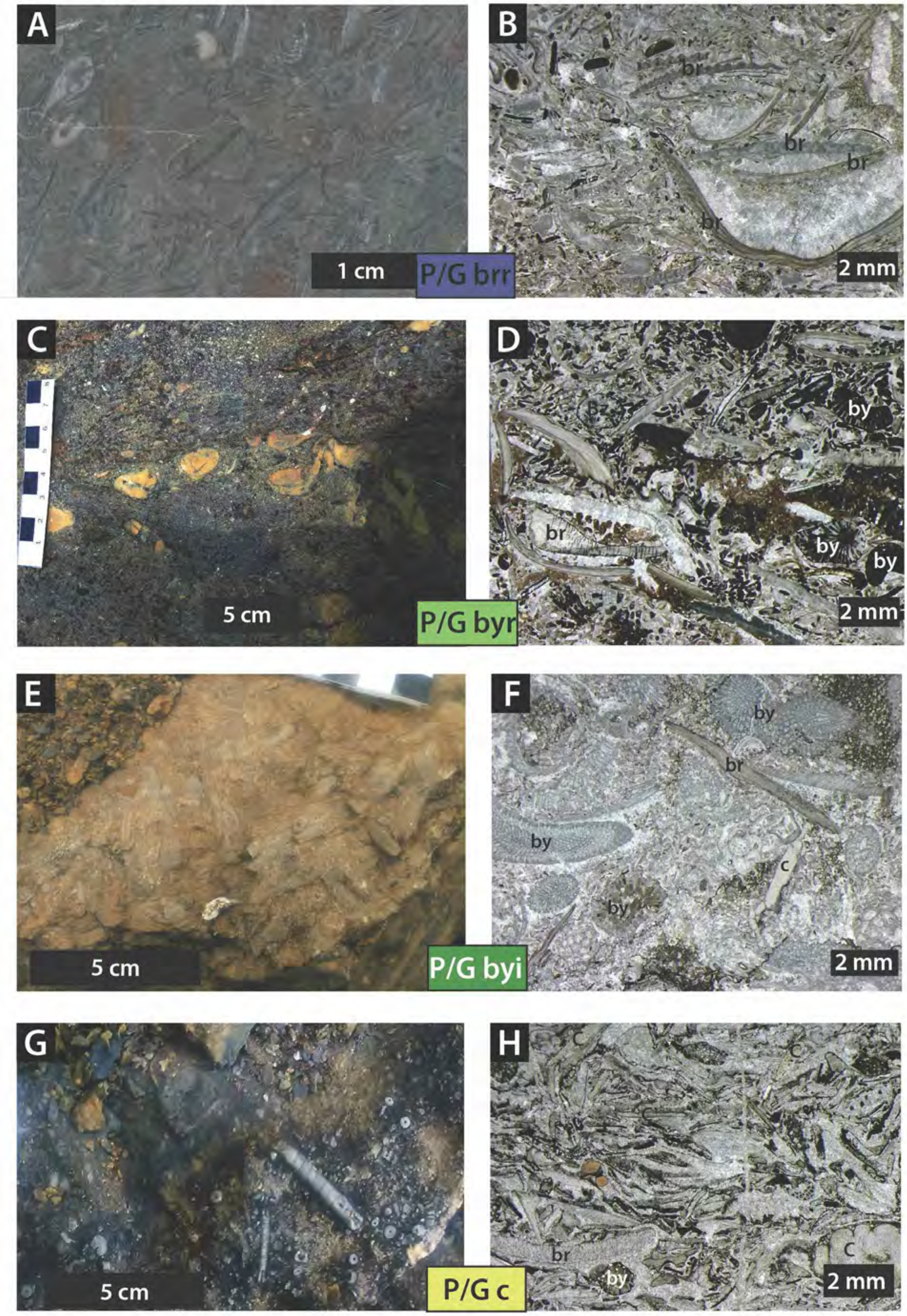

**Fig. 7.-** A, B. Polished section and thin section image of the limestones with reworked brachiopods, facies P/G brr (br: brachiopods). C, D. Field image and thin section image of the limestones with reworked bryozoans, facies P/G byr facies (br: brachiopods, by: bryozoans). E, F. Field image and thin section image of the limestones with *in situ* bryozoans, facies P/G byi facies (by: bryozoans; c: crinoids). G, H. Field image and thin section image of the crinoidal limestones, facies P/G c (br: brachiopods, by: bryozoans; c: crinoids).

| Facies | C | S | Bm | Sl | P/G c | P/G byr | P/G byi | P/G brr | P/G bri | Ri |
|---|---|---|---|---|---|---|---|---|---|---|
| C | - | 0,215 | -0,110 | -0,052 | -0,062 | -0,107 | -0,039 | 0,133 | 0,022 | 37 |
| S | 0,665 | - | -0,034 | -0,045 | -0,102 | -0,142 | -0,034 | -0,273 | -0,028 | 16 |
| Bm | -0,153 | 0,021 | - | -0,046 | -0,044 | -0,143 | -0,034 | 0,310 | 0,089 | 17 |
| Sl | -0,201 | -0,092 | -0,092 | - | 0,027 | -0,011 | -0,033 | 0,429 | -0,027 | 8 |
| P/G c | -0,085 | -0,034 | -0,034 | 0,017 | - | 0,170 | 0,028 | -0,085 | 0,034 | 16 |
| P/G byr | -0,182 | -0,102 | -0,022 | - 0,048 | 0,052 | - | 0,124 | 0,207 | -0,030 | 25 |
| P/G byi | -0,199 | -0,091 | -0,091 | -0,043 | 0,237 | 0,199 | - | 0,016 | -0,027 | 6 |
| P/G brr | 0,006 | -0,099 | 0,047 | 0,051 | -0,009 | 0,050 | -0,030 | - | -0,038 | 62 |
| P/G bri | 0,002 | -0,091 | 0,309 | -0,043 | -0,096 | -0,134 | -0,032 | 0,084 | - | 5 |
| Rj | 37 | 17 | 17 | 8 | 18 | 25 | 6 | 59 | 5 | 192 |

**Table 2.-** Probabilistic matrix obtained after Markov Chain analysis, showing the probability of facies transitions. The most probable facies transitions are outlined in light blue. Ri: number of transitions from a facies to other, Rj: number of transitions from any facies to a concrete facies.

*Vertical facies stacking*. Most of the described facies are present and complexly intercalated along member d2a, but some of them have a specific distribution. This is the case of the sandstone facies (S), which occurs exclusively in the lower d2aα submember (Fig. 4), and of the bioclastic marls (Bm) and the P/G of *in situ* brachiopods (P/G bri) that are only present in the upper d2aβ submember (Fig. 5). The results of the Markov Chain analysis applied to unravel the most probable vertical facies transitions are summarized in Table 2. The facies transitions obtained are illustrated separately for submembers d2aα and d2aβ in Figure 8, as each submember includes a different suite of facies.

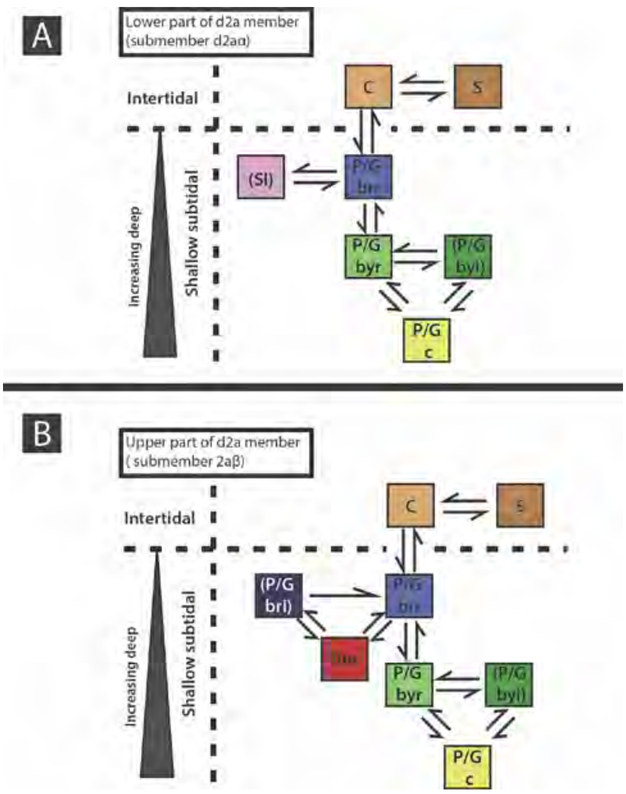

**Fig. 8.-** Vertical relationships between the described facies of the lower member d2a of the Nogueras Fm. Double arrows point out the alternation between facies, whereas a simple arrow indicates transition to top. The parenthesis marks occasional facies.

In submember d2aα (Fig. 8A), facies C (mudstones) and S (sandstones) are usually associated, being the sandstones exclusively related (intercalated) with the mudstones. The only carbonate facies that is clearly related with the mudstones is the P/G of reworked brachiopods (P/G brr), which usually are seen in the field as thin beds intercalated within the mudstones. The mixed facies Sl (sandy limestones) is related exclusively with the P/G of reworked brachiopods (P/G brr). This P/G brr facies is also related with the bryozoan facies P/G byr and byi, which are intercalated between them and with the P/G of crinoids (P/G c). Brachiopod and crinoid facies hardly ever are related.

In submember d2aβ, similar facies relationships than those recorded in d2aα have been obtained for terrigenous-clastic facies (C and S), P/G of reworked brachiopods (P/G brr), bryozoan facies (P/G byr and byi) and P/G of crinoids (P/G c) (Fig. 8B). However, instead of the sandy limestones (Sl), brachiopod marls (Bm) and P/G with *in situ* brachiopods (P/G bri) appear laterally related each other and with the P/G of reworked brachiopods (P/G brr).

*Sedimentary models*. The sedimentary features of facies and their vertical relationships (and lateral relationships during deposition, by the application of the Walther´s law) allow the interpretation of their subenvironments of deposition. Due to the different set of facies recorded in the two submembers d2aα and d2aβ (Fig. 8), two different sedimentary models with subtle differences have been proposed (Fig. 9).

The sedimentary model for submember d2aα includes an intertidal area dominated by the deposition of terrigenous-

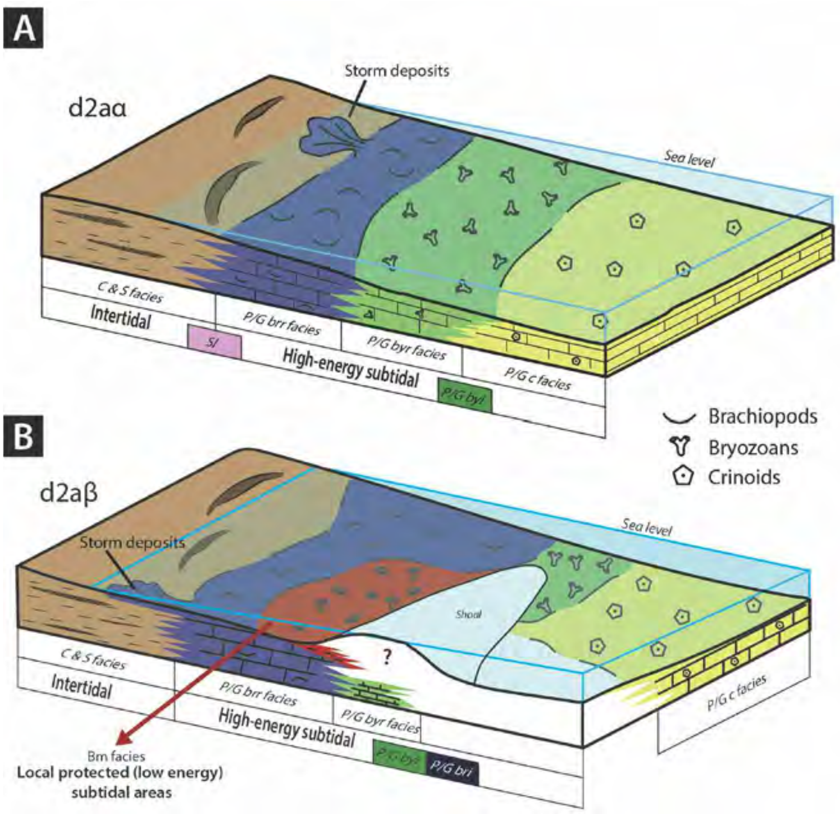

**Fig. 9.**- Sedimentary models proposed for submembers d2aα and d2aβ of the d2a member of Nogueras Fm, showing the lateral relationships of facies. Question mark indicates the probable position of the hypothetic shoals protecting low-energy areas where brachiopod marls (facies Bm) were deposited. Sandy limestones (facies Sl) are related to high detrital input, whereas limestones with *in situ* bryozoans and brachiopods (facies P/G byi and P/G bri) probably correspond to episodes of low sedimentation rates (also cemented substrates for P/G byi).

clastic sediments and a subtidal carbonate-dominated area (Fig. 9A). The terrigenous-clastic facies (C and S) represent the deposition of terrigenous muds in low energy conditions (C) and intercalated higher-energy coarser (sandy) sediments with ripples and cross-lamination (S). These facies fit well with the intertidal facies described in siliciclastic tidal flats, usually characterized by the alternation of muddy and sandy sediments with small bedforms (*e.g.*, Dalrymple, 2010).

The laterally related grain-supported carbonate facies (Fig. 8) are interpreted as subtidal sediments, including from proximal P/G brr facies (P/G of reworked brachiopods), to relatively distal bryozoan facies (P/G byr and P/G byi) and crinoid facies (P/G c), based on the deduced lateral facies relationships. Their grain-supported texture, the predominance in different proportions of bioclastic debris of brachiopods, bryozoans and crinoids, indicate deposition in high-energy conditions. Planar-, trough- and herringbone cross-bedding, local low-relief channelized bases, and parallel lamination defined by variation in grain size, are indicative of the migration of bedforms (megaripples/dunes) due to the action of tidal and/or wave currents within the shallow subtidal subenvironment. However, the limited lateral extent of outcropping beds and the tectonic deformation have prevented a more accurate analysis of the lateral extent of cross bedding and of the required paleocurrent measurement to decipher the predominance of tidal or wave flows in the shallow area.

High-energy conditions are also indicated by the presence of iron ooids (Table 1). Devonian iron ooids have been also described in the Cantabrian Mountains (NW Spain) as original iron ooids accumulated in high-energy shallow sublittoral environments, being the genesis of iron compounds related to the subaerial weathering of volcanic rocks (García-Ramos *et al.*, 1987). In the studied case, the obliterated internal microstructure of ooids has prevented to identify the original composition of ooid lamina (carbonate or iron minerals), and thus to decipher the degree of agitation based on the features of cortices of possible original carbonate ooids (*e.g.*, Strasser, 1986) or the involved genetic processes of possible iron ooids. The higher percentage of ooids within the relatively shallower P/G brr facies (Table 1) points to they originate in shallow waters, rather that their generation in distal environments and resedimentation onshore related to condensed sections (*e.g.*, Collin *et al.*, 2005). Ferruginous crusts are also usually present, more frequently in the shallower P/G brr facies, and can be interpreted as generated by high-energy events that winnowed uncemented seabed sediments and exposed the underlying cemented substratum, rather than cemented surfaces generated during events of low sedimentation rates (Chris *et al.*, 2012). Presence of phosphate nodules in these facies and their generation linked with resedimentation processes in the shallow-water settings would be discussed in the next subsection.

The high-energy conditions in the shallow-water subtidal area is also indicated by P/G of reworked brachiopods (P/G brr) that are intercalated as thin beds within the intertidal mudstones (facies C), which would represent bioclastic accumulations in the intertidal zone, probably as the result of storm episodes. The sandy limestones (Sl), with planar-, trough- and herringbone cross-bedding and characterized by sand-rich and skeletal-rich laminae, were probably deposited in the intertidal-subtidal transition area, laterally related to both S and P/G brr facies. Herringbone cross-bedding is widely used as an indication of tidal deposition (Dalrymple, 2010). In addition, alternations of siliciclastic and bioclastic foreset strata, quite similar to that recorded in facies Sl, have been described in subtidal tidal bundles in sand-dominated tidal systems (Longhitano, 2011), but also in wave-dominated shallow water settings (Chiarella and Longhitano, 2012). The sandy limestones (SI) only appear in the basal part of the studied Nogueras Fm and can be interpreted as a transitional facies between the Luesma and Nogueras formations. The facies including *in situ* bryozoans growing on ferruginized sur-

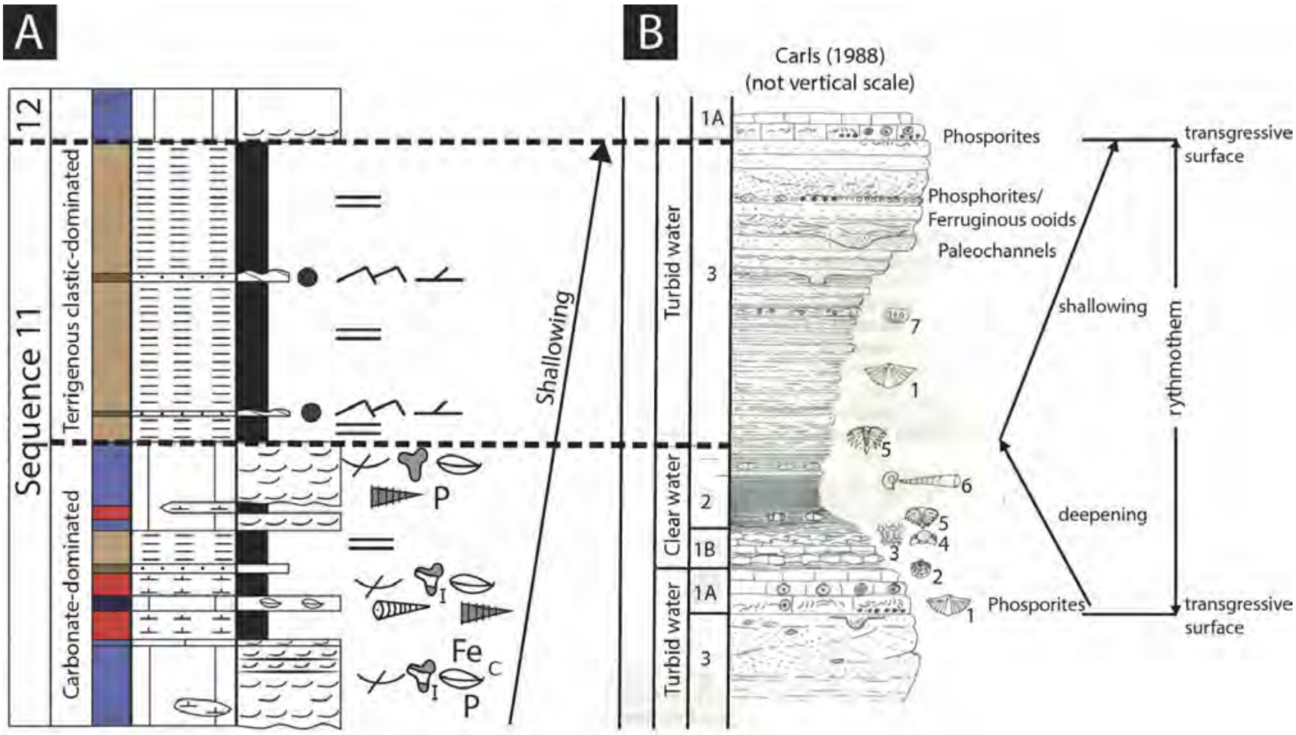

**Fig. 10.-** Comparison between (A) shallowing-upward sequence 11 (see location in left column in Fig. 5) and (B) a (deepening-shallowing) *rythmothem* reillustrated from Carls (1988). The *rythmothem* (without vertical scale in the original figure), include the following fossil groups: 1) turbid water (Rhenish) brachiopods, 2) clear water (Bohemian) brachiopods, 3) Fenestelid bryozoans, 4) clear water trilobites, 5) turbid water trilobites, 6) pelagic fauna (cephalopods), 7) ostracods. Note that both in sequence 11 and the *rythmothem*, carbonate sediments are located at the lower part, whereas terrigenous-clastic shallow-water facies dominate at the upper part. Nevertheless, these clastic deposits are low-energy (intertidal) facies in the sequence and high-energy facies in the *rythmothem*.

faces (P/G byi) is very occasional and is interpreted as the local colonization of hardened subtidal P/G byr sediments.

In the sedimentary model for submember d2aβ, the brachiopod marls (Bm) would be in lateral relationship with the brachiopod limestones (facies P/G brr and bri), as indicated by the abundance of brachiopods in all these facies. There are two possible subenvironments for these brachiopod-rich mixed muddy sediments (Bm): 1) small ponds within the intertidal domain; however, this is in disagreement with the Markov Chain analysis, as facies Bm is not related with the intertidal facies C and S (Table 2 and Fig. 8); or 2) subtidal sediments located in protected - low energy- areas laterally related with the brachiopod limestones (P/G brr and bri), an interpretation that is coherent with the Markov Chain results. The existence of protected, low-energy subtidal areas would be due to possible shoals developed seaward (Fig. 9B), although in the studied outcrops facies potentially representing high-energy barriers (*e.g.*, facies with large-scale cross-bedding) have not been recorded. Facies of *in situ* brachiopods (P/G bri) is an occasional facies that appears in the subtidal domain, in relationship with the brachiopod marls (facies Bm) and P/G brt (Fig. 8B). These facies bearing articulate brachiopod shells (Bm and P/G bri) are studied in detail in the paleontological analysis.

*Sedimentary sequences.* Considering the paleoenvironmental interpretation of facies, at least 14 facies sequences can be recognized in the lower member d2a of Nogueras Fm (Figs. 4 and 5). The sequences are very variable in thickness (around 4 m in average) and most of them are shallowing-upward sequences (from dominant carbonate subtidal facies at the lower part to terrigenous-clastic intertidal facies on top; Fig. 10A). The vertical arrangement of clastic and carbonate facies in these sequences represents a 'true' mixed clastic-carbonate system, instead of episodes of reciprocal sedimentation controlled by external factors (*e.g.*, see discussion in Schwarz *et al.*, 2016). The upper boundary of each sequence is a deepening surface, from shallower to relatively deeper facies that can contain phosphate nodules. However, phosphate nodules and phosphatized fossils are also present throughout the carbonate intervals of sequences, more frequently within the relatively shallower packstone/grainstone of reworked brachiopods (facies P/G brr; Figs. 4, 5 and 10A). This points out that phosphatization was probably related to different stages of remobilization and remineralization of dissolved phosphate derived from continental weathering in shallow water sediments, rather than phosphate-enrichment due to coastal upwelling during possible transgressive episodes (*e.g.*, Dornbos, 2011; Filipelli, 2011), proposed for the studied unit by Carls (1999).

The significance of the recorded shallowing sequences is out of the scope of this work and would require the analysis and correlation of sequences in separate sections. The studied upper Lochkovian succession is around 40 m in thickness and encompasses an uncertain time interval of some Mys (the entire Lochkovian spans around 7.7 Mys: Da Silva *et al.*, 2016). This data indicated reduced accumulation rates and subsidence, already suggested by Carls (1999). The recorded sequences have an uncertain duration, within the range of

3th-order or 4th-order sequences of Vail et al. (1991) and their origin linked to tectonic pulses of accommodation gain or sea-level cycles is open to discussion. The presence of a serrated cm-depth irregular paleokarst surface on top of the crinoidal P/G in sequence 2 (Fig. 4), is a local evidence of subaerial erosion associated to a sea-level fall, thus indicating the possible link of some sequences to low-amplitude eustatic sea-level cycles in the greenhouse Early Devonian epoch.

The sequences correspond to carbonate/terrigenous-clastic facies sequences similar to the *rythmothems* described by Carls (1988, 1999) for the Silurian and Devonian strata (Fig. 10B); however, in the studied sequences neither the deeper, low-energy mudstones facies described within the *rythmothems* (interval 2 in Fig. 10B) nor the high-energy sandstone facies (interval 3 in Fig. 10B) have been recorded. Instead of shallow high-energy sandstone facies, intertidal mudstones and fine sandstones (facies C and S) have been recognized.

### *Paleontological analysis*

*Description.* The taxonomic and taphonomic analysis of fossil groups has been carried out with invertebrate fossils collected and identified during fieldwork, especially those of Bm and P/G bri facies, and with invertebrate and vertebrate fossils observed in thin-sections. They were recognised and identified at least at Order level, using as reference the work of Herrera and Villas (2013) about the fossils of the studied unit. Concerning invertebrate fossils, trepostomate bryozoans displaying branching and hemispheric morphologies, crinoids, tentaculitids and orthocerid nautiloid cephalopods have been recognized. Brachiopods are the most abundant and diverse group and include the following orders and genera: Orthida (*Platyorhis*, *Isorthis*, *Schizophoria)*, Spiriferida (*Howelella*), Strophomenida, Terebratulida (*Megantherys*, *Neopaulinella*), Rhynchonellida (*Uncinulus*) Athyridida and Atrypida. Bm facies beds that have been sampled for fossils (Fig. 5) show the highest fossil diversity, with remains of all of the invertebrate groups described, except crinoids. In thin section fossils of ostracods, trilobites and bivalves have been observed too. Vertebrate remains are scarce, and have been only identified in thin section. They correspond to conodonts and fish remains, specifically dental elements. In the area, several remains of conodonts and chondrichthyes, thelodonti, acanthodian and placoderm fishes have been described (Botella and Valenzuela-Ríos, 2002; Botella *et al.*, 2006, 2009, 2012), so it is reasonable that the fossil observed in the present work belong to one of these groups, but no further analysis has been carried out.

The presence of a calcareous bed bearing a great accumulation of fossils, mostly brachiopods (bed 46) belonging to *in situ* brachiopod limestones (subtidal facies P/G bri), has allowed a more detailed taxonomic and taphonomic analysis (Fi. 11). The large exposure if its top surface allowed a taxonomic counting using a grid of 25x25 cm to extrapolate the relative abundance of each group in the whole bed. The results of this counting are reflected in Figure 12. The bed is clearly dominated by orthid brachiopods (62 %), including three main genera: *Isorthis* (Or1): with biconvex shells with fine ribs, *Platyorthis* (Or2), with plano-convex shells with fine ribs, and *Schizophoria* (Or3), with large dorsibiconvex and thicker ribs. The second main group of brachiopods are terebratulids (13%), all of them belonging to *Megantherys* genus. Other groups of brachiopods are athyrids (9%) and spiriferids (8%). Finally, bryozoans, atrypids and strophomenid brachiopods, crinoids and gastropods are also present in less proportion. In summary, bed 46 (subtidal facies P/G bri) has a high diversity of brachiopods, belonging to the main Devonian brachiopod groups (Clarkson, 1979).

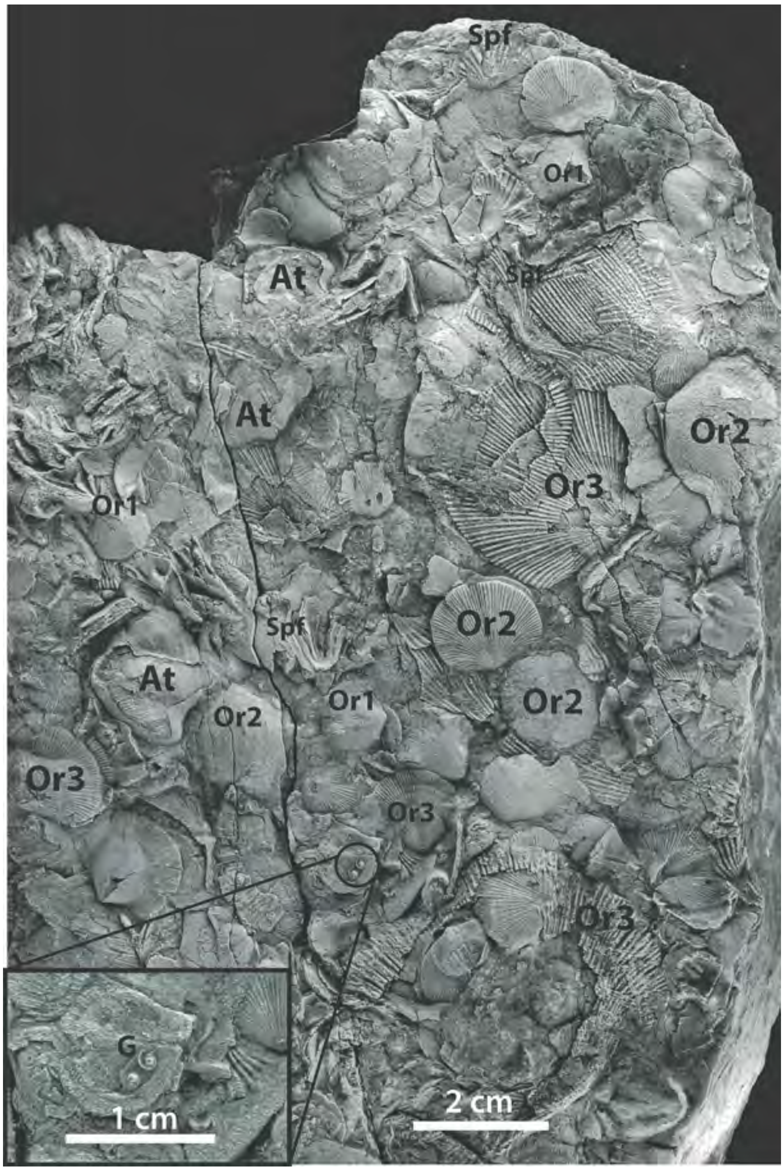

**Fig. 11.-** Representative sample of bed 46 (see location in Fig. 5). At: athyrids, G: gastropods, Or1: Isorthis, Or2: Plathyorthis, Or3: Schizophoria, Spf: spiriferids. In this sample there are not any terebratulids.

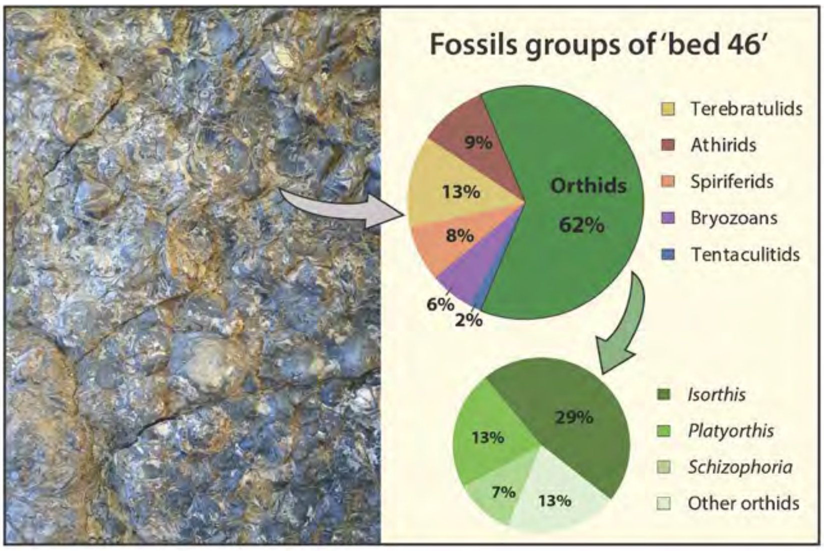

**Fig. 12.-** Diagram showing the relative abundance of the different fossil groups in bed 46.

The taphonomic analysis of brachiopod fossils in bed 46, included the study of features such as shell articulation/dislocation, size and shape selection, degree of fracturing, trend of concavity/convexity of valves and the amount of dorsal and ventral valves preserved, which allow to obtain complementary information about the depositional subenvironment of facies P/G bri. Taphonomic features have been also studied in other less abundant groups (Table 3). Thus, the fossil groups of bed 46 have been divided, according to the terminology of Kidwell *et al.* (1986), in: 1) autochthonous/parautochtonous fossils (well-preserved fossils, with poor sorting, articulated or little fractured shells, and sometimes in life position) that might live within or near the depositional subenvironment; and 2) allochthonous fossils (generally disarticulated and fragmented, well sorted and scarce), carried from their life subenvironment to a foreign one. Autochthonous/parautochtonous fossils (90% of the fossils) include orthid, terebratulid and athyrid brachiopods and bryozoans. Allochthonous fossils (10% of the fossils) encompass spiriferid and strophomenid brachiopods and crinoids.

*Interpretation.* After the paleontological study complemented with the sedimentological analysis, some paleoecological information on the main fossil groups within the shallow marine depositional environment can be inferred. Firstly, a clearly zonation can be deduced according to the facies distribution (Fig. 8), with brachiopods living in the shallowest area of the subtidal domain, crinoids dominating in the relatively deeper area, whereas bryozoans would occupy an intermediate position. Besides, fossil abundance and diversity in the brachiopod marls (facies Bm) support the sedimentological interpretation of facies Bm as low-energy protected areas in the platform (protected hypothetically by shoals) where brachiopods thrived on muddy sediments, rather than ponds within the intertidal area. According to the fossil assemblages of Boucot (1975), intertidal areas are characterized by fluctuating low- and high energy conditions and scarce diversity of organisms, with only a few specialist forms, whereas in the subtidal areas the diversity increases, as is the case of facies Bm.

The taphonomic analysis of the *in situ* brachiopod limestones (subtidal facies P/G bri) in bed 46 displays a population of autochthonous-parautochthonous organisms (90% in total), and minor proportion of allochthonous organisms (10%). The absence of bioclast lineations and the predominance of oriented valves with convexity oriented upwards (Table 3, orthids) point up that the shells where accumulated in an environment with certain turbulence, but not submitted to a continuous agitation. So, we can conclude that the P/G bri facies represents deposition in subtidal areas with possible alternating low- and high-energy conditions and/variations in sedimentation rates: episodes of low-energy conditions and/or minor sedimentation rates favoured the seabed colonization by brachiopods and other organisms, whereas high-energy conditions would bury or slightly drag the shell remains, and bring allochthonous skeletal remains from nearby areas. It is reasonable to think that this P/G bri facies, as well as the brachiopod marls (facies Bm) were the source area of skeletal remains recorded in the limestones bearing transported brachiopods (facies P/G brt).

| Group | Taphonomic features | Interpretation |
|---|---|---|
| Orthids | Poor sorting (0.5-5 cm)<br>Disarticulated shells<br>Low fracturation degree (35%)<br>Dorsal/Ventral (51%/49%)<br>Domination of convexity upwards (88%) | Autochthonous-parautochthonous |
| Terebratulids | Poor sorting (0.5-2 cm)<br>Entire shells<br>Life position (33%) | Autochthonous-parautochthonous |
| Athyrids | Poor sorting (0.8-1.5 cm)<br>Generally entire shells | Autochthonous-parautochthonous |
| Spiriferids | Good sorting (1-1.2 cm)<br>Entire shells to fragments | Allochthonous |
| Strophomenids | Disarticulated and fragmented<br>Scarce presence | Allochthonous |
| Bryozoans | Life position<br>Brachiopods shells as substratum | Autochthonous-parautochthonous |
| Crinoids | Isolated ossicles<br>Scarce presence | Allochthonous |
| **% Autochthonous-parautochthonous vs allochthonous** | | **90% vs 10%** |

**Table 3.-** Taphonomic features of the main fossil groups of bed 46, pointing out their autochthony or allochthony.

Finally, it is relevant to highlight that the organism collected and studied present adaptions for repelling coarse siliciclastic sediment, as could be zig-zag commissures of spiriferids and rhynchonellids (*Uncinulus*), or athyrid wrinkles. The clearly absence of hermatipic corals (that usually thrive in clear waters) also reinforces the interpretation of a turbid-water environment with suspended clays and silts that would reduce water transparency, similar to previous interpretations (Carls, 1988; Carls and Valenzuela-Ríos, 2002), identifying the fossils from the Nogueras Fm as Rhenish fauna, adapted to the described conditions.

## Conclusions

Nine sedimentary facies have been recognized in the lower member of the Nogueras Fm (d2a), according to lithology, texture, main components and sedimentary structures: terrigenous-clastic facies (mudstones and sandstones), mixed facies (brachiopod marls and sandy limestones) and carbonate facies (packstones/grainstones of transported and of *in situ* brachiopods, packstones/grainstones of transported and of *in situ* bryozoans and packstones/grainstones of crinoids). Based on their vertical distribution, two sedimentary models for submembers d2aα and d2aβ have been proposed encompassing the shallow areas of a mixed clastic-carbonate system.

The sedimentary model for submember d2aα shows two main domains: a terrigenous-clastic intertidal zone (mudstones and intercalated fine-grained sandstones) and a carbonate-dominated shallow subtidal zone with predominant high-energy conditions (skeletal limestones with packstone/grainstone texture). The main skeletal grains changes according to their position in the subtidal zone: brachiopods dominate in shallower areas, crinoids dominate in relative distal areas, and bryozoans occupy an intermediate position. Mixed terrigenous-carbonate deposits (sandy limestones) related with episodes of high detrital input. The model for submember d2aβ includes similar intertidal sediments, but some specific facies in the subtidal zone, in particular brachiopod marly deposits. These marls are related to calm areas of the subtidal zone probably protected by shoals. Phosphate nodules, phosphatized fossils, ferruginous crusts and iron ooids, which are frequently associated with the relatively shallower bioclastic brachiopod facies, were probably linked continental sources and to remobilization in the shallow water high-energy area. The defined facies are arranged in shallowing-upward sequences (from subtidal carbonate-dominated sediments to intertidal clastic-dominated deposits) of uncertain origin and duration ($3^{th}$-order or $4^{th}$-order sequences; tectonic pulses or sea level cycles). They do not show the relative deep mudstone facies and the high-energy sandstone facies included in the *rythmothems* described by Carls (1988, 1999) for the Silurian and Devonian strata.

The paleontological study has pointed the main groups of organisms that inhabited this platform during the Early Devonian. Fossil sampling has allowed identifying a great diversity of organisms, predominantly brachiopods, associated to local protected environments of the subtidal zone (brachiopod marls) and subtidal zones with alternating low- and high-energy conditions (limestones with *in situ* brachiopods). Taphonomic analysis also points a differentiation between autochthonous/parautochtonous organisms (most of them brachiopods: orthids, terebratulids, athyrids and bryozoans) and allochthonous (spiriferids and crinoids) in the limestones with *in situ* brachiopods. This study represents a preliminary paleontological analysis for future paleoecological studies describing the communities associated to each of the defined facies/subenvironments, where rich ecosystems of orthids, terebratulids, spiriferids and other groups developed.

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