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Facies patterns and depositional processes in two Frasnian mixed siliciclastic-carbonate systems in the Cantabrian Mountains, northwest Spain

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Abstract

Relative sea level fluctuations during the Frasnian generated two shallow-marine, mixed siliciclastic-carbonate successions in the Devonian Asturo-Leonese Basin. Each system represents a third-order sequence-stratigraphical unit deposited in the same basin during comparable extreme greenhouse conditions without nearby fluvial entry points. Depositional control on the siliciclastic and carbonate distribution was driven by relative sea level fluctuations, basin geometry, availability of sand and the way sediment was distributed by shelf currents. Early Variscan flexural bending of the continental crust changed the basin shape from a shelf with a gradual profile and low dip (early Frasnian) towards a shelf with a steep depositional dip (late Frasnian). Shelf distribution changed from along-shelf transport (early Frasnian) towards offshore-directed gravity flows (late Frasnian). As a consequence, siliciclastic-carbonate distribution changed from a predominance of skeletal carbonate in the proximal shoreface – foreshore area and siliciclastic predominance distally (early Frasnian), to a distribution pattern with proximal shoreface skeletal carbonates, offshore muddy carbonates and a siliciclastic zone in between where gravity flows distributed the siliciclastic sediment down dip (late Frasnian).

Key words: mixed systems, sequence stratigraphy, depositional controls, Upper Devonian, Asturo-Leonese Basin

1. Introduction

Mixed siliciclastic-carbonate systems are characterised by variable coeval input of both carbonates and siliciclasts (Zeller et al., 2015; Schwartz et al., 2018). Depositional models for shallow-marine, mixed siliciclastic-carbonate systems are still poorly understood. Even within one climate regime and within the same basin, mixed systems can be highly variable (Schwartz et al., 2018). A wide range of controlling processes, which can vary in space and time, determine the sedimentary input of both systems, which include climate, carbonate factory, siliciclastic supply and shelf transport. The two Frasnian units in the Asturo-Leonese Basin, the Gordón Member and Millar Member, provide an opportunity to compare two mixed depositional systems within the same basin, each with their characteristic carbonate-siliciclastic distribution along the Frasnian shelf transect, in which both vertical and lateral transitions occur from carbonate to siliciclastic predominance. Together they span the entire Frasnian. The basin was formed as a result of early Variscan foreland basin development (Keller et al., 2008; Van Loevezijn & Van Loevezijn-Peña, 2017). Each Frasnian unit, representing a third-order sequence (*sensu* Vail et al., 1977), formed during extreme greenhouse conditions (Joachimski et al.,

2009) in a shallow-marine setting. Both units have comparable thicknesses ranging between 80 and 120 metres (Van Loevezijn & Van Loevezijn-Peña, 2017). The aims of the present study are twofold: to reconstruct the mixed Frasnian siliciclastic-carbonate systems in the southern Cantabrian Mountains in detail along their depositional dip and to explore their depositional controls.

2. Geological setting

2.1. Cantabrian Zone

The Palaeozoic deposits of the Cantabrian Mountains are part of the Cantabrian Zone – the northern thrust and fold belt of the Iberian Massif (Lotze, 1945; Pérez-Estaun et al., 2004) (Fig. 1A). The present geological setting is the result of Late Carboniferous nappe tectonics.

The Cantabrian Zone can be subdivided into three main palaeogeographical units: the Asturian geanticline (Van Adrichem Boogaert, 1967) or Cantabrian Block (Radig, 1962), the Asturo-Leonese facies area and the Palentine facies area (Fig. 1B). The core of the Cantabrian Zone consists of the Asturian geanticline, an area characterised by the near-complete absence of Silurian and Devonian strata, and the clastic source area of the surrounding Devonian sedimentary basin. The Asturo-Leonese facies has a shallow and proximal character where coarse detritic sediments of the Asturian geanticline were deposited. The pelagic Palentine facies suggests deposition in distal deeper areas, has an allochthonous character and is restricted to the Variscan Palentine nappes in the southeast. In the outermost part of the Asturo-Leonese facies area, the External Zone of Van Loevezijn (1986), a complete Upper Devonian succession, up to 650 metres in thickness, occurs (Fig. 1C). The zone is bounded to the north by the Intra Asturo-Leonese facies line (IAL facies line) of Raven (1983). It separates the External Zone from an area with a thin, incomplete Upper Devonian succession. The stratigraphical interval studied comprises the Frasnian succession of the Asturo-Leonese facies area of the southern Cantabrian Mountains.

2.2. Stratigraphy

During the Early to Middle Devonian and prior to the onset of Variscan orogeny the Cantabrian Zone hosted a shallow-marine environment on a stable extensive shelf, with a mixed sedimentation of carbonates and siliciclastics, fed from a continental landmass in the core of the Cantabrian Zone, the Asturian geanticline (Van Loevezijn, 1989; Fernan-

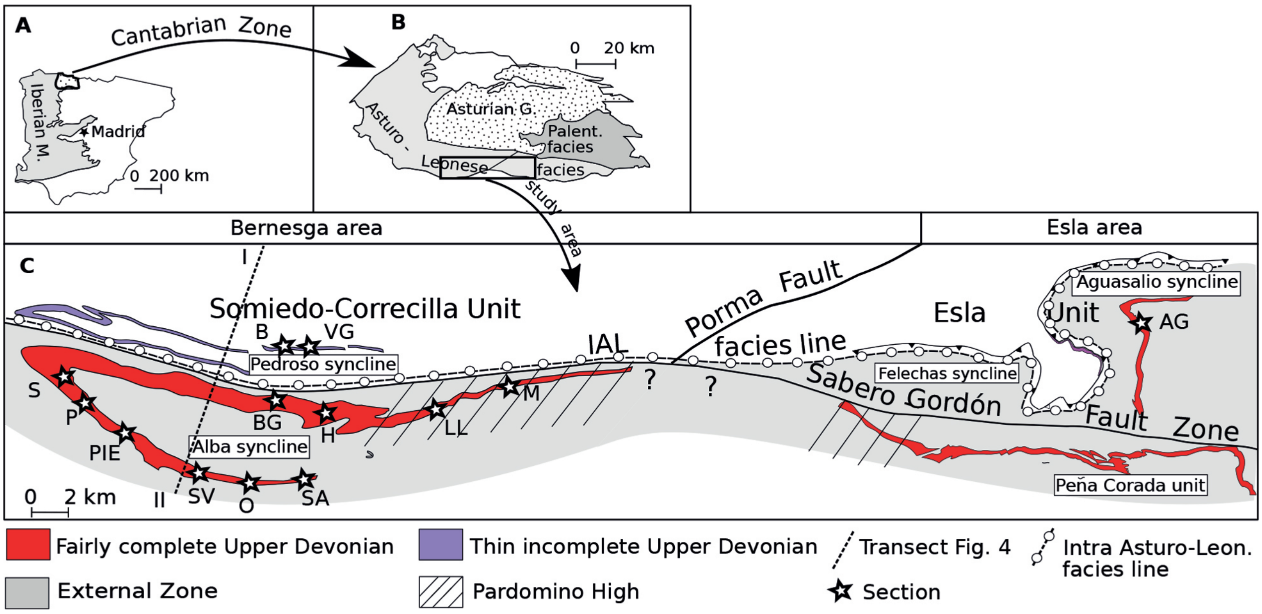

Fig. 1. A – Situation map of the Iberian Peninsula with the Iberian Massif and the Cantabrian Zone indicated; **B** – Map of the Cantabrian Zone, with major palaeogeographical units; **C** – Geological map of the study area with location of sections, tectonic units and palaeogeographical units. AG – Aguasalio section; M – Matallana de Torío section; Ll – Llombera de Gordón section; H – Huergas de Gordón section; BG – Barrios de Gordón section; SA – Sorribos de Alba section; O – Olleros de Alba section; SV – Santiago de las Villas section; PIE – Piedrasecha section; P – Portilla de Luna section; Sagüera de Luna section

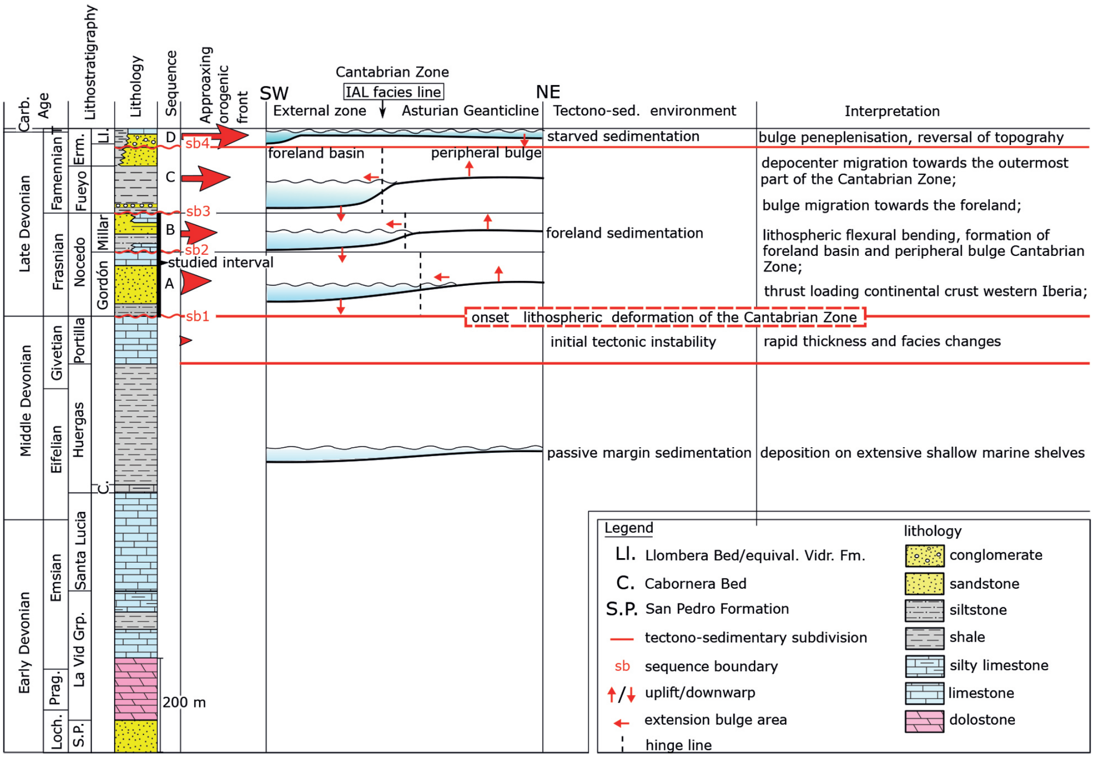

Fig. 2. Devonian stratigraphy of the Asturo-Leonese facies with the tectono-sedimentary development and topography of western Iberia

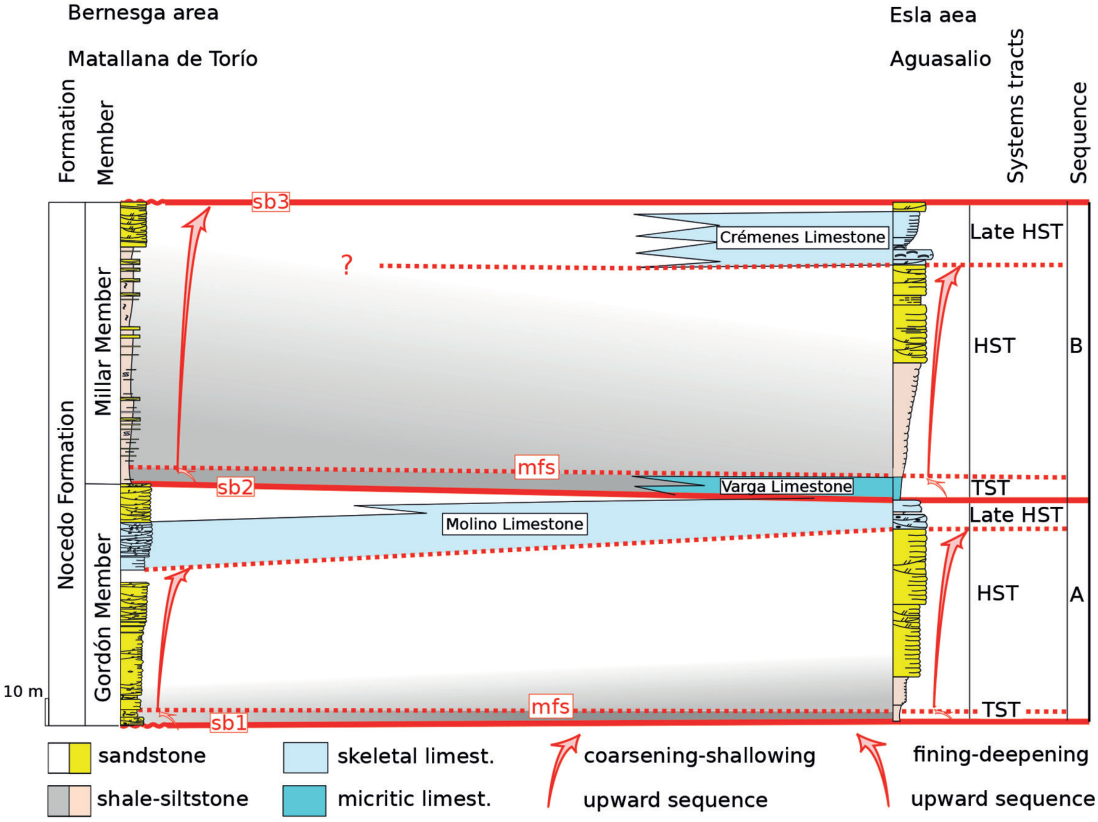

Fig. 3. Correlation of Frasnian deposits in the Bernesga and Esla areas
TST – transgressive systems tracts; HST – highstand systems tracts; mfs – maximum flooding surface; sb – sequence boundary.

dez Martinez et al., 2010), resulting in a stratigraphical succession of reef and siliciclastic formations (Fig. 2). Late Devonian tectonic movements started to change the stable basin configuration.

The shelf transformed into a southern trough with rapid subsidence (External Zone) and a tilted northern area of uplift and erosion. The depositional area shifted towards the distal parts of the Asturo-Leonese shelf, whilst the inner part of the shelf emerged. The erosional products formed three Upper Devonian clastic wedges in the External Zone of the Asturo-Leonese basin (Van Loevezijn, 1986). The two Frasnian depositional wedges are included in the Nocedo Formation of Comte (1959). This formation crops out in the Alba and Pedroso synclines of the Somiedo-Correcilla thrust complex, in the Peña Corada unit and Aguasalio syncline of the Esla thrust complex. It has been subdivided into a lower Gordón Member and an upper Millar Member (Van Loevezijn, 1983), each containing a siliciclastic, coarsening-upwards sequence overlain by a limestone unit; a sandy crinoidal unit, the Molino Limestone of the Gordón Member (García López & Sanz-López, 2002), and a coral-stromatoporoid reef unit, the Crémenes Limestone (Westbroek, 1964) within the Millar Member (Fig. 3). Furthermore, in the basal part of the Millar Member, a dark micritic limestone unit occurs, the Varga Limestone (Van Loevezijn & Raven, 2017). The Molino Limestone has an extensive geographical distribution; the Varga and Crémenes limestones are restricted to the eastern part of the Esla area. Palaeogeographical pre-Variscan reconstructions must be treated with caution, because of tectonic shortening and erosion of the Palaeozoic sequence (Fig. 4).

2.3. Biostratigraphy

The uppermost limestones of the Portilla Formation underlying the Nocedo Formation contain conodonts of the Givetian *hermanni-cristatus* Zone (Garcia López & Sanz-López, 2002). The Molino Limestone in the upper part of the Gordón Member yields a rich conodont fauna. Garcia López & Sanz-López (2002) recognised the upper *falsiovalis* to the lower *hassi* zones (Fig. 5). The calcareous intercalations of the Górdon Member above the Molino Limestone contain conodonts which correspond to the upper *hassi* Zone. The approximately 20-m-thick Crémenes Limestone in the uppermost part of the Millar Member has a rich coral-stromatoporoid reef fauna of pre-Famennian, Frasnian age (Van Loevezijn et al., 1986). Conodonts are rare and it is difficult to correlate the Crémenes Limestone with the standard conodont zones. The main por-

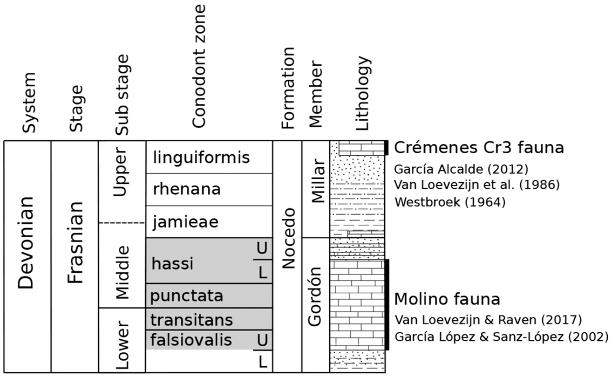

Fig. 5. Frasnian lithology and faunal elements, with recognised conodont zones shaded grey. Succession is scaled to conodont zones

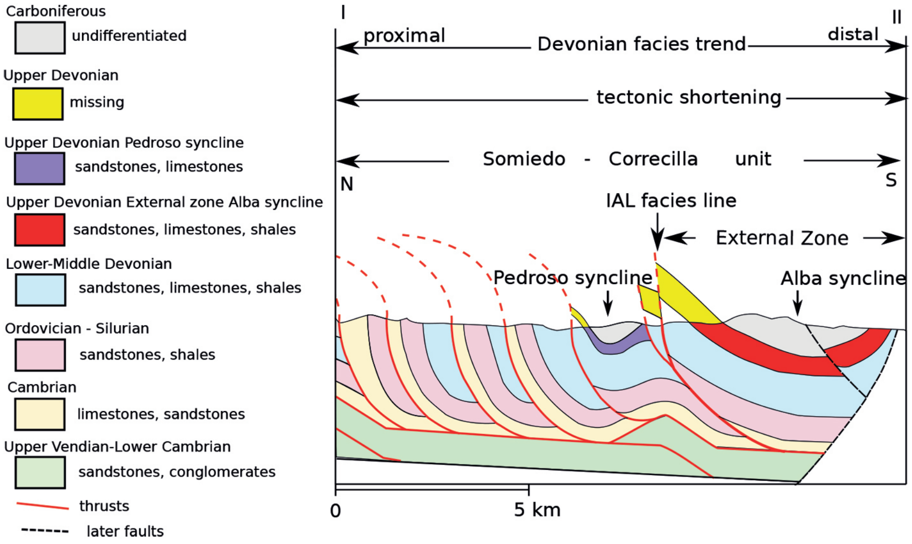

Fig. 4. Structural N–S cross section of the Bernesga area with the Devonian facies trends, tectonic shortening and the Upper Devonian highlighted (vertical scale exaggerated; changed after Veselovsky, 2004)

Table 1. Description and interpretation of Frasnian facies associations

Facies		Lithology, sedimentary structures	Components, fossils	Interpretation	Env.	
					C.	S.
		Offshore				
Carbonate mudstone	⬛🟦	Dark grey massive carbonate mudst., 0.3–2.0 m beds, bitumenous	Macrofossils uncommon, few Atrypa spec.	Deposition from suspension, minimal physical reworking, poorly oxygeneted sea floor conditions, offshore zone	■	
Carbonate mudst.-shale	▤🟦	Purple calc. shale, carbonate mudst. lenses, very fossiliferous	Abundant brachiopods, bryozoans	Low net accumulation rate, minimal physical reworking, offshore zone	■	
Laminated shale	▤⬜	Gr. brwn laminated shale, few mm silt streaks	Few brach., crinoids	Deposition from suspension, low-ener., offshore zone		□
		Transition				
Thin-bedded shale-siltstone rhythmites	▤🟨	Silty shale with mm to 10 cm thick silty very fine -grained sandst. beds, erosive base, f.u., ripple laminated, bioturbation	Few brach., crin.	Fair weather mud, sandy distal storm event deposition below fair weather wave base, transition-offshore zone		□
Thick-bedded shale-sandstone rhythmites	▤🟧	Up to 0.5 m thick beds of very fine to fine-grained sandst., scour bases, up to 5 m wide shallow channels, hummocky cross-stratification	Few brach., crin.	Storm-related suspension flows, below normal wave base		□
Bioturbated siltstone	▤🟧	Brwn nodular calcareous sandy siltst., heavily bioturb., shale flaces, thixotropic deformation	Abundant brach., crin., bryozoans, solitary coral	Low bottom energy cond., reg. suply of sand and silt, intens. colonization benthic comm., well oxyg. sea floor, trans. zone		□
		Lower shoreface				
Bioturbated silty sandstone	▨🟨	Grey brwn, thick to massive bedded , havily bioturbated, silty ,very fine-grained sandst., shale laminae, mottled, ferruginous, rare hummockey cross-lamination	Fe ooids, brach., crin.	Well-oxygen. low-energy environment, close to fair weather wave base, lower shoreface zone		□
Quartz arenite	▨🟨	L. grey to yellow, very fine to fine-grained, medium to thick bedded quartz arenite, slightly bioturbated, rare cross-bedding	Shale flaces, few crin.	Well oxygenated environment, some bioturbation, shoreface zone close to upper shoreface		□
		Upper shoreface				
Cross-bedded quartz arenite	▨🟨	L. grey to yellow, very fine to fine-rained qrtz arenite, tabular and trough cross-bedding low-angle lamination, weak bioturbation	Few crin., brach.	Turbulent coastal sand environment, migrating bars, tidal channels, upper shoreface zone		□
		Back-barrier				
Mottled silty sandstone	▨🟩	Grey brwn, nod., irregular bedded, calcareous, very fine-grained silty sandst., very bioturb., ferruginous mottled	Few brach., crin.	Low bottom energy cond., regular supply of sand and silt, intens coloniz. benthic commun., well oxyg. sea floor, mixed carb. silicicl., shelterd coastal zone		□

Facies	Lithology, sedimentary structures	Components, fossils	Interpretation	Env.	
				C.	S.
Shoal/reef				■	
Massive boundstone 🟦	L. grey, massive bedded, stromatop.-coral boundstones	Stromatoporoids, corals	High energy coral stromatoporoed reef environm., well oxyg., shoreface zone	■	
Argillaceous bafflestone bindstone 🟦	Grey red, nod. bedded, argill. bafflest. bindst.	Stromatop., corals, brach. bryoz., crin., ostrac., tril., pelecyp., gastr., receptac.	Coral stromatoporoid reef environment, well-oxyg., low energy bottom condit.	■	
Sandy grainstone 🟦	Grey brwn fine-grained cross-bedded biocl. grainstones, 10–50 cm beds, well-bedded, *skolithos* ichnofauna	Mainly bioclasts of crinoids, brachiopods	Turbulent coastal mixed carb. silicicl. sand environment of the shoal fringe, upper shoreface zone	■	
Coarse bioclastic grainstone 🟪	Red to purple very coarse-grained bioclastic grainstones, cross-bedded, erosion surfaces, ferruginous coating and impregnation	Abundat skelet. debris of brach., crin., bryoz., cor., intraclasts, coated grains	High energy shoal core, winnowed lag, erosion, reworking, upper shoreface z.	■	
Fine-grained bioclastic grainstone 🟦	L. brwn fine-grained bioclastic grainst., few very fine grained sand admixed, 20–30 cm beds, well-bedded, mud drapes, bioturbation	Bioclasts of crin., brach., undeterminable fragm.	Medium energy coastal environment, shoal fringe, upper shoreface zone	■	
Silty wackestone packstone 🟩	Red, nodular, thin bedded, mottled silty wackest., packst., very fine-grained sand	Thin-shelled small foss., brach., crin., corals, gastr.	Low-energy, well-oxygenated, sheltered area of the open lagoonal zone	■	
Bioclastic mudstone wackestone 🟩	Grey, nodular, 1–10 cm bedded, fossiliferous wackest., black bitum., 20 cm bedded mudst.	Crin., brach., oysters, gastropods, corals	Stagnated non-turbid water, periodical fresh water inflow, open lagoonal z.	■	

C – carbonate predominance; S – siliciclastic predominance, hssc – high suspended sediment concentrations.

tion of the Crémenes brachiopod fauna indicates a Frasnian age, but some Famennian forms are also explicitly present (CR3 fauna). Subsequent palaeontological investigation by García Alcalde (2012) has underlined the ambivalent character of the fauna, with brachiopod species from the Frasnian and others (thus far) only known from the Famennian. The paucity of conodonts and the mixed signals of the brachiopod fauna inhibit unambiguous dating of the Crémenes Limestone, but the available data indicate late Frasnian to early Famennian. Therefore, the top of the Nocedo Formation is probably close to the Frasnian-Famennian boundary.

3. Facies associations

During the last decades several publications have dealt with Upper Devonian lithofacies associations of the southern Cantabrian Mountains: the facies model of the Molino Limestone (Van Loevezijn & Raven, 2017), the Crémenes Limestone (Van Loevezijn et al., 1986) and the Frasnian-Famennian facies pattern of the Bernesga area (Van Loevezijn & Van Loevezijn Peña, 2017). In the present paper the emphasis is on facies stacking patterns of siliciclastic and carbonate sedimentary rocks related to Frasnian ramp-slope evolution of the Asturo-Leonese facies area. All the Frasnian facies types are summarised, to provide a complete facies picture of the southern Cantabrian Mountains; new facies types are introduced and some existing facies types had to be split, for optimal Frasnian facies differentiation (Table 1).

The facies types can be arranged into six facies associations, each representing distinct depositional conditions across the shelf. All Frasnian deposits are composed of an admixture of siliciclastic and carbonate sediments and facies types are classified according their dominant lithology.

3.1. Offshore facies association

This association is composed of three facies types: carbonate mudstone, carbonate mudstone-shale and laminated shale. The first two are restricted to the Varga Limestone in the Esla area (Fig. 3).

Description. Carbonate mudstone: This facies type is composed of dark grey to black massive-bedded bituminous carbonate mudstone with a structureless appearance. Macrofossils are uncommon; a few brachiopods (*Atrypa* sp.) occur. Bioturbation is very sparse.

Carbonate mudstone-shale: this heterolithic facies type consists of purple calcareous shales, with intercalations of carbonate mudstone-wackestone lenses containing large numbers of bryozoans and brachiopods.

Laminated shale: finely laminated fissile, grey-brown shale, locally with intercalations of thin (1- to 3-mm-thick) silt layers. This rock is of low bioturbation and poor in fossils; occasionally thin-shelled brachiopods and crinoids occur.

Interpretation: The siliciclastic and carbonate muds suggest very low bottom energy conditions allowing the finest fraction to settle down from suspension. No evidence is found of traction currents; cross-lamination does not occur and no coarse sediment was introduced into this environment. Current activity must have been extremely weak. Deposition of dark to black bituminous sediment is related to an oxygen-deficient environment (Lüning et al., 2004). The black carbonate mudstones and grey laminated shales are interpreted as the product of suspension deposition on a poorly oxygenated sea floor. This resulted in the dark grey and black colour of the sediment (sulphides) and the paucity of benthic fauna. The carbonate mudstones represent the outermost offshore setting, far from siliciclastic supply, where sedimentation rate was very low and where a condensed carbonate mud succession could develop from carbonate particles dropping out of suspension. The laminated shales were deposited within the area of supply of siliciclastics from suspension, where thin silt intercalations represent suspension load from storm-generated flows transported into the offshore area and with a poor macrofauna. The fossiliferous heterolithic carbonate-shale deposits settled from suspension on a well-oxygenated low-energy sea floor, just below storm-wave base, and have a rich benthic fauna. In this distal setting siliciclastic supply was high enough to dilute carbonate sedimentation temporarily.

3.2. Transition facies association

This association comprises three facies types: the thin-bedded heterolithic shale-siltstone facies type, the thick-bedded heterolithic shale-sandstone facies type and the bioturbated homogeneous silt facies type.

Description: Thin-bedded shale-siltstone alternation: fine-grained siliciclastic deposits with grey-brown laminated shales and siltstones and intercalations of thin-bedded sandstone. The main portion of the sandstone deposits consists of very fine to fine-grained, millimetre- to 10-cm-thick, graded sandstone beds with an erosional sharp base, a structureless or parallel to subparallel laminated lower part, overlain by a wave-ripple-laminated succession with common escape structures and with a gradational bioturbated silty top. Background sediment consists of laminated fair-weather silty shales (Fig. 6). Slump structures, load structures and convolute bedding occur.

Thick-bedded shale-sandstone alternation: sand-rich heterolithic deposits with grey-brown bioturbated silty shales, alternating with up to 0.5-m-thick, very fine-grained sandstone beds (Fig. 7). Hummocky cross stratification, up to 5-m-wide channels and massive structureless sandstone beds occur, interbedded with heterolithic thin-bedded shale siltstone successions.

Bioturbated siltstone: brown, nodular, sandy calcareous argillaceous siltstones. The sediment is intensively bioturbated and completely reworked, causing a nodular mottled appearance (Fig. 8). Shale flakes occur in the sediment. These strata contain abundant brachiopods, bryozoans, crinoids and solitary corals.

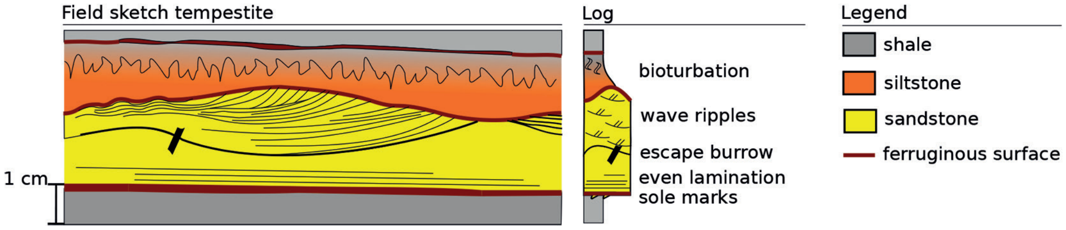

Fig. 6. Field sketch of a distal tempestite, with even lamination and climbing ripples, topped by upward-fining bioturbated mudstone: Millar Member sequence B, Matallana section

Interpretation: The heterolithic facies types indicate contrasting energy conditions. The large proportion of fines suggests energy conditions low enough to allow mud deposition, and bioturbation indicates well-oxygenated sea floor conditions. Trace fossils of the sediment feeders (*Cruziana*) reflect deposition in the shallow subtidal zone between fair weather wave base and storm wave base (Reineck & Singh, 1975). The intercalated graded and laminated sheet sandstones indicate a much higher depositional energy. Escape burrows in the basal part of the sandstone beds suggest rapid deposition. Water escape from the sediment suspension resulted in penecontemporaneous deformation structures. The sharp flat basal and top surfaces, the horizontal and wavy lamination, the grading and the contrasting depositional energy conditions suggest tempestite deposition in the quiet, low-energy environment of the transition zone close to storm wave base (Vierek, 2013). Erosional surfaces suggest reworking by bottom currents; the sediment gravity currents of the tempestites. The bed thicknesses up to 10 cm, the absence of basal lags and conglomeratic fabrics and the very fine grainsize of the sandstone beds are diagnostic of the distal position of the tempestites (Aigner, 1985; Myrow & Southard, 1996; Vierek, 2013). The thick, up to 0.5 m, sandstone beds of the thick-bedded shale-sandstone alterations were formed in a more proximal position, where storm surge flows created shallow channels and hummocky bedforms. The thin- and thick-bedded facies types reflect a storm-dominated environment of the transition zone between the offshore and shoreface zones as described by Einsele (2000).

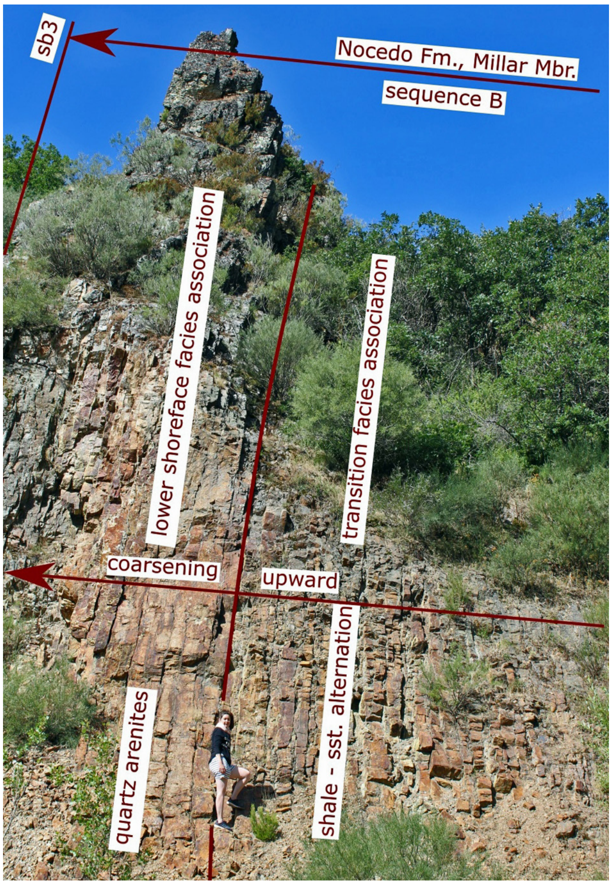

Fig. 7. Sheet sandstone beds with sharp basal and top surfaces, alternating with bioturbated siltstones of the transition facies association, grading upwards into quartz arenites of the lower shoreface facies association. Coarsening-upward succession of sequence B, Millar Member, Nocedo Formation, Llombera section

Fig. 8. Intensely reworked, completely bioturbated, nodular siltstone of the transition facies association: Huergas de Gordón section

The bioturbated siltstone facies reflects a low-energy environment allowing mud deposition, with a regular supply of silt and sand from the shoreface. The siltstones were deposited in the transition zone between the sandy shoreface zone updip and the muddy offshore zone downdip. Very intense bioturbation homogeneously mixed the silt and very fine-grained sand and completely destroyed primary bedding (Reineck & Singh, 1975), causing the nodular appearance of the mixed sediment (Fig. 8).

3.3. Lower shoreface facies association

This association comprises two facies types: the bioturbated silty sandstone facies type and the quartz arenite facies type.

Description: Bioturbated silty sandstone: this facies type grades vertically from the underlying bioturbated siltstone facies type and consists of grey-brown, mottled, very fine-grained quartz sandstone, locally with a small portion of siltstone. Bioturbation is the most characteristic feature, resulting in a homogeneous massive and structureless sandstone. Locally the bio-reworking of the sediment created a mottled pattern with shale flakes. In this environment physical sedimentary structures are faintly preserved. Amalgamated sandstones beds with shallow channel structures occur with low-angle wavy cross-lamination. Locally some ripple structures are preserved in the sandstones (Fig. 9). Cross-bedding is uncommon.

Fig. 9. Fairly bioturbated, silty to very fine-grained sandstones with wave ripple structures of the lower shoreface facies association: Huergas de Gordón section

Fig. 10. Well-bedded quartz arenites of the lower shoreface facies association, with channel structures: Huergas de Gordón section

Massive quartz arenite: this facies type grades vertically from the bioturbated sandstone facies and is overlain by the cross-bedded quartz arenite facies. It comprises light grey to yellow, very fine to fine-grained, medium- to thick-bedded quartz arenites. Cross-bedding is uncommon. Locally, channel structures can be observed in the quartz arenites (Fig. 10). The sediment is moderately bioturbated.

Interpretation: The gradational lower contact with the facies types of the transition zone indicates a relationship with the low-energy environment close to fair weather wave base. The bioturbated silty sandstone packages indicate deposition in a lower shoreface setting composed of very fine sand with small amounts of silt, close to fair weather base with sufficient sand supply, and with very intense biogenic reworking (Reineck & Singh, 1975). The absence of a fine-grained fraction in the overlying quartz arenites reflects that fines, if ever deposited, were not preserved. This suggests that quartz arenites of this facies type were deposited in more energetic water flows in slightly agitated water. However, cross-bedded structures are scarce, reflecting deposition outside the upper shoreface currents of bars, troughs and rip channels. Therefore, the massive quartz arenites are interpreted to reflect the transition from the bioturbated sandstones of the lower shoreface zone to the cross-bedded quartz arenites of the upper shoreface zone.

3.4. Upper shoreface facies association

This facies association consists of a single facies type: the cross-bedded quartz arenite facies type.

Description: Cross-bedded quartz arenite: this facies association is composed mainly of light grey to yellow, very fine to fine-grained, cross-bedded quartz arenites. Locally iron-stained red coloured quartz arenites occur. Both trough cross-sets and tabular cross-sets occur, locally arranged in herringbone structures. Low-angle laminated sets occur in the upper part of the quartz arenite successions. Bioturbation is usually absent, or is represented by sparse escape burrows of the *Skolithos* ichnofacies (filter feeder). The facies is poor in fossils; mostly sparsely distributed bioclasts of brachiopod shells and crinoid ossicles. This facies is often underlain by the sandstones of the lower shoreface facies zone. Skeletal sandy grainstones of the shoal facies association occur locally in the upper part of the cross-bedded quartz arenites.

Interpretation: The mineralogically and texturally mature sediments reflect deposition in a turbulent environment where fines were washed out. The abundant cross-bedded structures and channels indicate an agitated environment with shifting sediment loads. The low bioturbation and the escape burrows suggest an unstable mobile substrate; the sediment was constantly reworked by powerful sediment-shifting currents. No fines could settle in this turbulent environment. The bimodal current directions are indicative of a tidal-influenced current system (Rossie & Steel, 2016). The low-angle cross-laminated sets were formed by swash and backwash in the foreshore zone. The facies association reflects deposition in the coastal sand environment of the upper shoreface and foreshore, with migrating sandbars and tidal channels.

3.5. Backshore – open lagoonal facies association

This facies association consists of a single facies type: the mottled silty sandstone facies type.

Description: Mottled silty sandstone: this facies type comprises grey-brown, heavily bioturbated calcareous, very fine-grained sandstones with a varying silt content. Bedding is poorly developed, and bioturbation resulted in complete homogenisation of the sediment and destruction of primary sedimentary structures. Locally, the sediment contains a ferruginous mottled appearance. In the fine sediment brachiopods and crinoids occur. This sediment facies type is often intercalated within the upper shoreface cross-bedded coastal sands.

Interpretation: The bioturbated fraction within these rocks suggests low bottom energy conditions allowing deposition of fines. The correlation with the cross-bedded coastal sands suggests deposition in a shallow-marine zone, probably on the land side of barriers islands or bars, and sheltered from the high-energy shoreface environment.

3.6. Shoal-reef facies association

This association contains a wide range of lithofacies types; massive boundstone, argillaceous bafflestone and bindstone, sandy grainstone, coarse bioclastic grainstone, fine-grained bioclastic grainstone, silty wackestone and packstone and bioclastic mudstone and wackestone.

Description: Massive boundstone: this facies type consists of light grey coloured, massive bedded, coral-stromatoporoid boundstones. The facies is restricted to the Crémenes Limestone in the uppermost part of the Millar Member (Fig. 3).

Argillaceous bafflestone and bindstone: this facies consists of nodular, grey-red coloured, argillaceous coral-stromatoporoid bafflestones and bindstones, with large numbers of brachiopods. Like the massive boundstones, this facies is restricted to the Crémenes Limestone in the uppermost part of the Millar Member (Fig. 3).

Sandy grainstone: this facies type is composed of grey-brown to red, very fine to fine-grained sandy grainstones with gradations to calcareous quartz sandstones, well stratified with 10-50-cm-thick beds, frequent cross-bedding with trough and tabular cross sets and channel incisions. Bioturbation is low and represented by sparse burrows of the *Skolithos* ichnofacies suite. Skeletal clasts of crinoids, brachiopods, bryozoans and trilobites occur.

Coarse-grained bioclastic grainstone: these sediments consist of red to purple coloured very coarse-grained bioclastic grainstones with a varying siliciclastic content, organised in 20-50-cm-thick beds with wavy sharp bedding surfaces. Tabular and trough cross-bedded sets, channels and erosion surfaces occur frequently, associated with intraclasts and ferruginous coated grains. The ferric oxides occur as coatings on various allochems and as impregnation of bioclastic pores. This facies type contains large quantities of echinoderms, clasts of brachiopods, corals, bryozoans, gastropods and tentaculites.

Fine-grained bioclastic grainstone: this facies type comprises grey to light-brown coloured, fine-grained bioclastic grainstones, organised in well-stratified, usually 10-cm-thick, but locally up to 20 cm, beds, with slightly erosive bedding surfaces. The beds are locally enclosed by cm-thick, bioturbated shale drapes. The sediment contains bioclasts of brachiopods and crinoids.

Silty wackestone and packstone: this facies type is composed of nodular, thin-bedded, wackestones and packstones with a varying silt content of up to 50%. The sediments are grey or red, often with a mottled pattern. Locally, the sediment is mixed and homogenised due to intense bioturbation. In some sections a gradual transition towards the overlying sediments of the cross-bedded sandy limestones can be observed. The facies type contains thin-shelled brachiopods, small crinoids, solitary corals, gastropods and coralline demosponges.

Bioclastic mudstone and wackestone: this facies type is composed of grey coloured, thin- (1-10 cm) to medium- (5-20 cm) bedded carbonate mudstones and fossiliferous wackestones, with less than 10% siliciclastics admixed. The fossils consist of crinoids, brachiopods, oysters, gastropods, and branching and solitary corals. This facies type often occurs in between the silty wackestone-packstone type (underneath) and the cross-bedded sandy and bioclastic grainstones (overlying).

Interpretation: sediments of the shoal-reef facies association occur in the Molino and the Crémenes limestone (Fig. 3), representing shallow-marine, carbonate-dominated environments of the mixed systems. The association can be subdivided into reef and shoal deposits. The boundstone and bafflestone-bindstone facies types reflect a stromatoporoid-coral reef environment (Van Loevezijn et al., 1986). These deposits are always underlain by sandy crinoidal grainstones. Devonian bio-constructed reef deposits often contain a sandy crinoidal grainstone succession sandwiched between the reef succession and the underlying siliciclastics; a feature that can be observed in several Devonian reef developments of the Cantabrian Mountains (Van Loevezijn, 1987; Méndez- Bedía et al., 1994). Crinoid debris probably stabilised the siliciclastic sea floor substrate prior to the development of reefs.

The overlying massive boundstones were formed in the shallow turbulent part of the reef ("Zone turbulente" of Lecompte, 1970), whereas the muddy baffle and bindstones are associated with the deeper part of the reef area ("Zone sousturbulente" "Zone subturbulente" of Lecompte, 1970).

The shoal deposits contain a broad range of lithologies, arranged into coarsening-upward, small-scale cycles of approximately 20 m, with silty mud-supported limestones at the base, followed by cross-bedded sandy grainstones and overlain by the very coarse-grained bioclastic grainstones (Fig. 11). The silty wackestone-packstone and bioclastic mudstone- wackestone facies types in the base of the small-scale cycles are grouped in an open lagoonal, depositional environment, sheltered by a bar or barrier, with low-energy bottom conditions allowing mud deposition. The dark mud-supported sediment suggests semi-restricted, non-turbid, quiet water conditions. The fossiliferous intercalations suggest a more favourable, oxygenated, bottom environment (Remane & Schlieper, 1971; Schlager, 2005). This was created by periodical water exchange with the open sea. The overlying sandy cross-bedded grainstones and the fine bioclastic grainstones display a mixing of carbonate and siliciclastic deposits. They were deposited at the edge of the shoal core just outside the highest energy zone, and represent the transitional area towards the deeper siliciclastic environment (shoal fringe: sandy grainstones) and towards the protected open lagoonal zone (shoal fringe: fine-grained bioclastic grainstones) (Van Loevezijn & Raven, 2017).

The coarse bioclastic grainstones in the top of the small-scale cycles represent an agitated, very turbulent shallow-marine shoal environment with a low sedimentation rate as indicated by the cross-bedded sets, erosive surfaces and intra-clasts (Fig. 12).

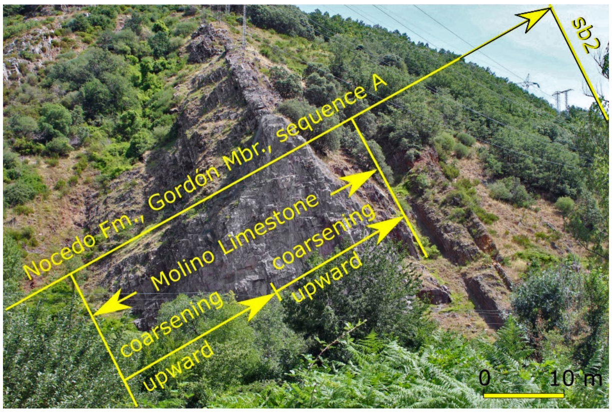

Fig. 11. Sandy bioclastic limestones of the shoal facies association, developed as two coarsening-upward, small-scale cycles: upper part of Gordón Member, Huergas de Gordón section

Fig. 12. Cross-bedded bioclastic grainstone of the shoal facies association: Molino Limestone, upper part of Gordón Member, Nocedo Formation, Matallana de Torío section

The cross-bedding contains strong bimodal current direction patterns, indicating tidally influenced currents (Rossie & Steel, 2016). These sediments represent the shallowest and most turbulent zone of the carbonate shoal.

4. Sequences

Changes in relative sea level during the Frasnian created the accommodation space for two coarsening-upward sequences, sequence A (Gordón Member) (Fig. 13) and sequence B (Millar Member). Both sequences are bounded by surfaces that present abrupt basinward facies shifts and have sharp, often erosional, features with a regional extension. The bounding surfaces (sequence boundaries) are labelled sb1 to sb3. Detailed cross-sections of sequences A and B of the Bernesga area, oriented

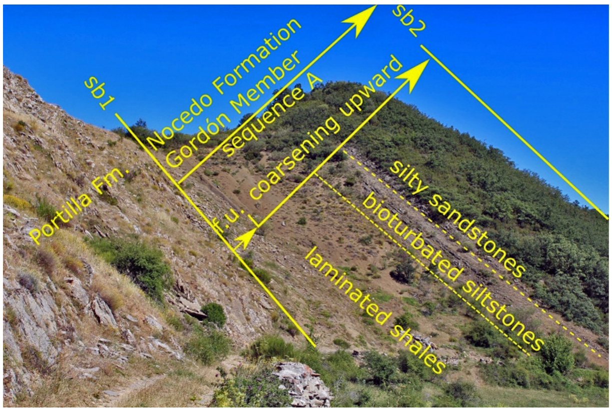

Fig. 13. Coarsening, shallowing-upward succession of the Gordón Member, sequence A, consisting of a well-developed laminated shale unit of the offshore facies association, a bioturbated siltstones unit of the transition facies association and a bioturbated sandstone unit of the lower shoreface facies association: Barrios de Gordón section

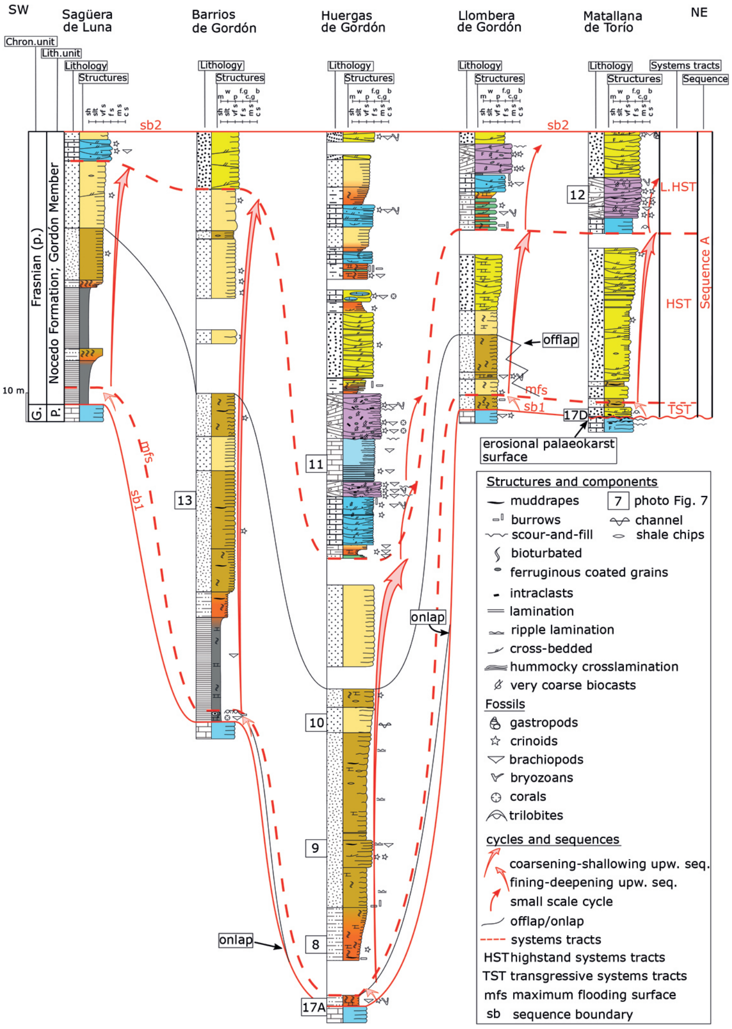

Fig. 14. Facies correlation panel of the Gordón Member, sequence A, Bernesga area, showing the sequence-stratigraphical boundaries, the coarsening- and fining-upward cycles and the onlap and offlap stratigraphical relations. Legend in Table 1

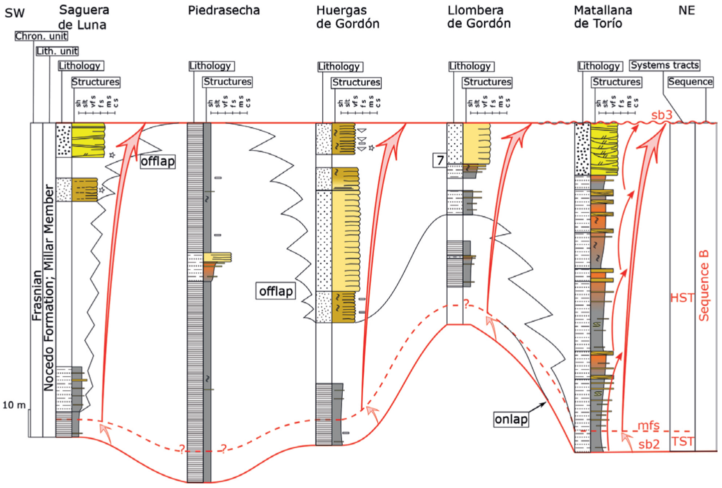

Fig. 15. Facies correlation panel of the Millar Member, sequence B, Bernesga area, showing the sequence-stratigraphical boundaries, the coarsening- and fining-upward cycles and the onlap and offlap stratigraphical relations. Legend in Table 1 and Figure 14

approximately along the NE-SW depositional dip, show the transgressive systems tracts (TST), highstand systems tracts (HST) and late highstand system tracts (Late HST) (Figs 14, 15). Both sequences fall into the third-order sequence range of Vail et al. (1977). For a more detailed description of the Frasnian sequence stratigraphy, the reader is referred to papers by Van Loevezijn & Van Loevezijn Peña (2017) and Van Loevezijn & Raven (2017).

5. Spatial facies distribution

Relative sea level changes on the mixed carbonate-siliciclastic platform are manifested in shifts of distinct facies belts and are interpreted in terms of sequence stratigraphy. Frasnian basin evolution will be explained by the spatial facies patterns of subsequent systems tracts of the Bernesga area; the Devonian core area of the southern Cantabrian Mountains. The large open Alba syncline of the Bernesga area suffered the lowest degree of shortening and deformation of all nearby tectonic Cantabrian units (Veselovsky, 2004) (Fig. 4), which supports the reliability of the palaeogeographical reconstructions.

5.1. Sequence A-TST

In the southwest, the TST sedimentary rocks consist of laminated shales of the offshore facies (Fig. 16A). Towards the northeast transitional siltstones and shoreface sandstones onlap sequence boundary 1 (Figs 16A, 17A). The shoreline transgressed towards the emerged area in the north and east, where bioturbated calcareous sandy siltstones filled an erosion surface of 20-m-wide channels in the top of the underlying Portilla Formation. The Nocedo siltstones locally penetrate into the underlying carbonates, filling karst fractures in the wall of the channels, are exposed in the road section north of Beberino (Fig. 17B, C). The section furthest to the east, a thin (10–25 cm) orange-coloured silt-mud unit at the base of the TST envelops an irregular, clearly erosive, karst surface (Fig. 18: unit 2) in the uppermost part of the underlying Portilla limestones (Fig. 17D). Overlying calcareous sandstone beds contain erosion products of the Portilla Formation (Fig. 18: unit 3). The unit was formed during the initial transgression when a shoreface environment migrated into the subaerially exposed area of the Pardomino High. The erosion products of the transgression were deposited as a transgressive lag in the shoreface environment. In summary, the TST is represented by an onlapping succession of offshore shales, transitional siltstones and a shoreface succession that formed when the coastal area flooded the higher karst grounds in the northeast. From current directions in the cross-bedded shoreface sets a NW–SE shoreline position and a northeasterly directed transgression can be inferred.

5.2. Sequence A-HST

The HST depositional area extended outside the External Zone to the north, where a thin succession of calcareous bioturbated very fine-grained sand was deposited in a sheltered environment (Fig. 16B). In the External Zone sediments were laid down on a gradual depositional profile with a high-energy and turbulent upper shoreface environment in the

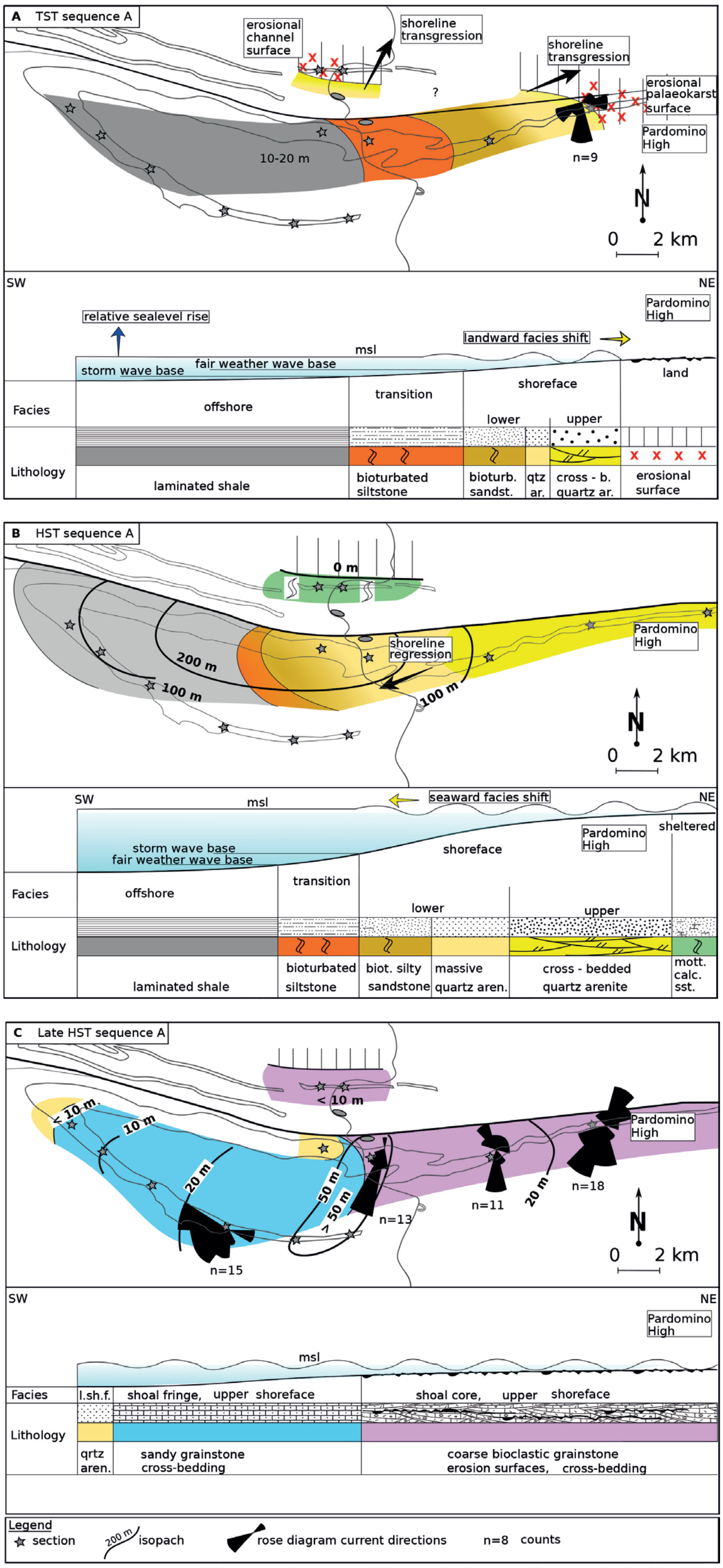

Fig. 16. A – Spatial facies zone reconstruction and depositional profile of the transgressive TST deposits, sequence A; **B** – Spatial facies zone reconstruction and depositional profile of the progradational HST deposits, sequence A; **C** – Spatial facies zone reconstruction and depositional profile of the late HST deposits, sequence A. Legend in Table 1. TST – transgressive systems tracts; HST – highstand systems tracts; msl – mean sea level; l.sh.f. – lower shoreface; biot. – bioturbated; cross-b. – cross-bedded; qrtz. aren. – quartz arenite

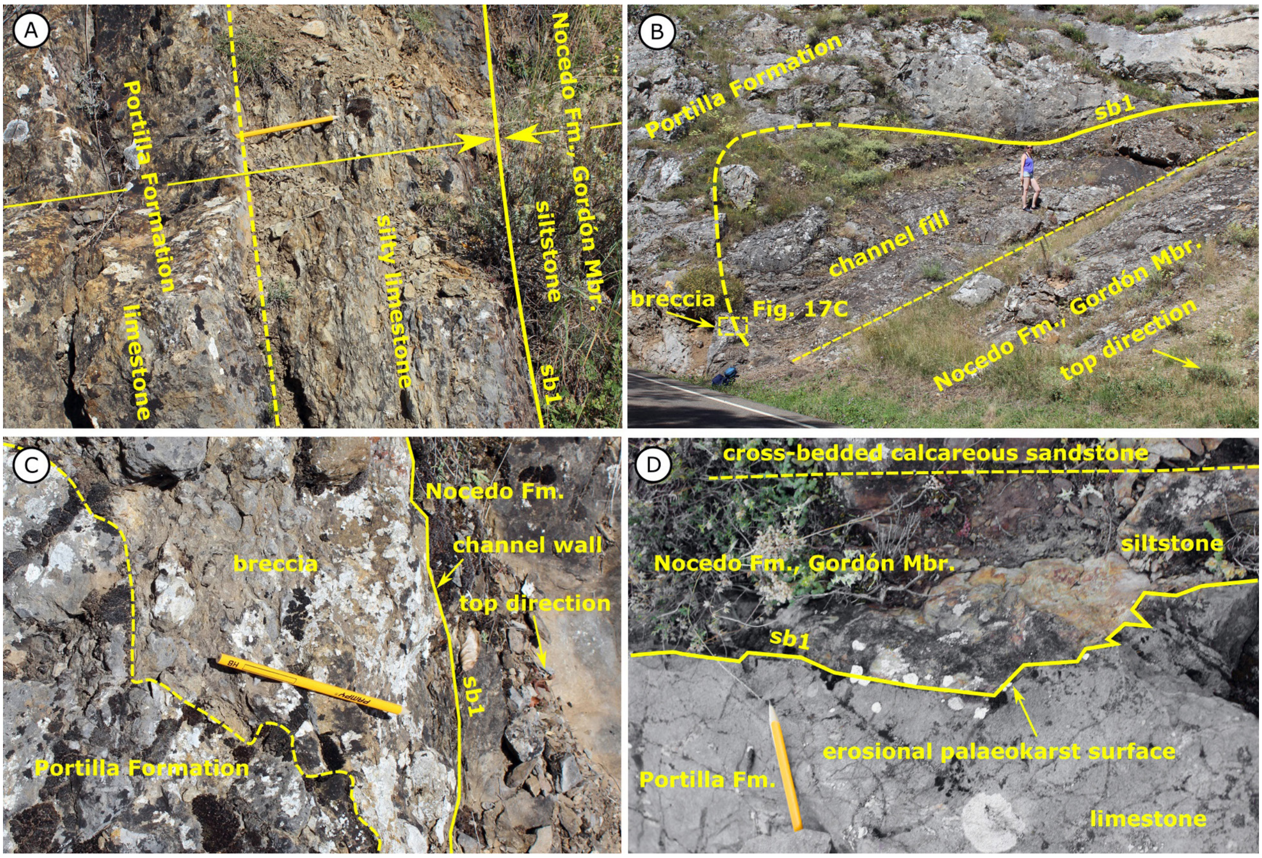

Fig. 17. Sequence boundary sb1. **A** – In the central area of the depositional basin, sb1 is a gradual contact between the limestones of the Portilla Formation and the overlying bioturbated siltstones or laminated shales of the Nocedo Formation: Huergas de Gordón section; **B** – Towards the north, close to the Asturian geanticline, the sb1 bounding surface has clearly erosional features with a remarkable relief, consisting of up to 20-m-wide erosive channels in the top of the Portilla Formation, mantled by light brown nodular calcareous sandy siltstone of the Nocedo Formation: Beberino section; **C** – Karst dissolution and crevices in the channel wall of the Portilla limestone (Fig. 17B) filled by Nocedo siltstone, limestone breccia: Beberino section; **D** – Close to the Pardomino High, sb1 represents an erosive palaeokarst surface mantled by the TST deposits of sequence A, Gordón Member, Nocedo Formation: Matallana de Torío section

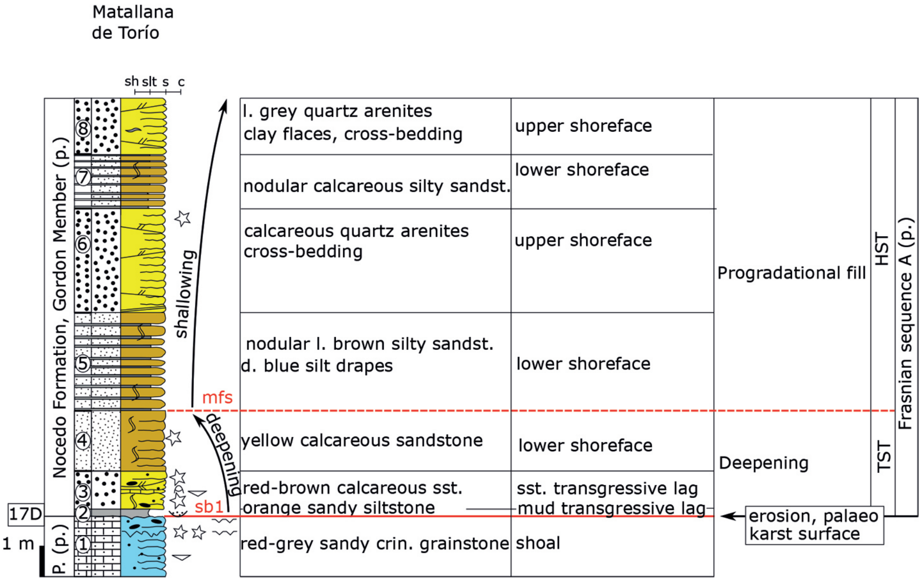

Fig. 18. Basal part of the Matallana section with palaeokarst surface indicated. Lithological units numbered 1 to 8. For legend see Table 1 and Figure 14

northeast, a lower shoreface zone in the centre of the area and an offshore area in the southwest. The depositional centre was located in the central part of the area; this consists mainly of a thick succession of lower shoreface sandstones. The bathymetrical centre of the basin was located in the southwest, where a succession of laminated shales of the offshore zone was deposited. The basinward progradation of the shallow-marine coastal area, resulted in a seaward facies shift and the formation of the coarsening-upward facies stack of sequence A, with offshore shales overlain by bioturbated siltstones of the transition zone. Above it, silty sandstones and massive quartz arenites of the lower shoreface occur, with an overlying offlapping succession of cross-bedded quartz arenites of the upper shoreface zone. The siliciclastic shallowing-upward succession is mixed with small amounts of skeletal carbonate.

5.3. Sequence A-Late HST

Current systems for effective sediment transport on gently inclined shelf profiles require a minimum water depth (Zeller et al., 2015). When progradation of the HST wedge consumed most of the accommodation space, water depth decreased and alongshelf currents, responsible for the shelf distribution of siliciclastic material, were forced into the outer (deeper) parts of the shelf. Shallow-marine siliciclastic sedimentation in the coastal area ceased, and a late HST shallow-marine skeletal carbonate shoal developed in a coarsening-upward succession, with carbonate muds of the sheltered facies zone, a coarse-grained bioclastic core, where erosion surfaces, intraclasts and bioclastic lag sediment indicate a very turbulent shallow-marine environment with constantly shifting substrate and low net sedimentation, and a cross-bedded sandy grainstone zone, which laterally merged into the siliciclastic zone of the deeper outer part of the shelf (Fig. 16C). The rose diagrams from the high-energy shoal core show a strongly bimodal pattern resulting from wave and tide currents perpendicular to the shore. The distal sandy grainstones indicate a near-unidirectional, along-shelf current parallel to the shoals.

5.4. Sequence B-TST

Net sedimentation retreated from the north and became restricted to the External Zone. The TST sediments represent a pronounced deepening of the basin: a thin succession of laminated offshore shales extended over the basin (Fig. 19A). Towards the Pardomino High the shales onlap sequence boundary 2 and are gradually substituted by thin-bedded tempestites of the transition zone. On the other side of the Pardomino High in the eastern Esla area, dark mud-supported limestones represent the distal offshore environment of the TST (Fig. 3).

5.5. Sequence B-HST

Close to the basin edge in the northeast and northwest, sands of the shoreface zone represent the HST (Fig. 19B). The centre of the basin was occupied by a storm-dominated, shallow- marine environment of the transition zone, where storms generated a 100-m-thick tempestite succession of sheet-like sand and silt beds with an updip-downdip pinch out. Solemark lineations on the lower surface of tempestite beds indicate a southerly to southwesterly sediment transport direction, parallel to the depositional dip and perpendicular to the palaeocoastline, as can be expected from sediment gravity flows (Einsele, 2000). The bathymetric centre was located in the southernmost part of the basin where mainly laminated shales of the offshore zone were deposited. Basinward migration of the shallow-marine coastal area, resulted in a seaward facies shift and formation of the coarsening-upward depositional wedge of sequence B with offshore shales in the basal part, overlain by storm-generated heterolithic succession of shale-siltstone alteration and topped by shoreface sandstones. In the Esla area the progradational wedge is capped by carbonate deposits of the Late HST, where carbonate shoals and coral-stromatoporoid reef limestones developed in the shallow-marine shoreface zone (Fig. 3).

6. Mixed carbonate siliciclastic systems

All Frasnian deposits are composed of an admixture of siliciclastic and carbonate sediments. Almost all siliciclastic sediments contain carbonate components and most of the carbonates contain siliciclastic grains, creating a variety of admixtures ranging from siliciclastic- to carbonate-dominated. Vertical facies stacking and lateral relationships between siliciclastic- dominated, mixed and carbonate-dominated associations have allowed reconstruction of the depositional controls in response to climate, carbonate factory, sediment supply, transport and tectonics. The Frasnian of the Cantabrian zone offers the opportunity to compare two different mixed siliciclastic carbonate systems within a single basin and under rather uniform climatic greenhouse con-

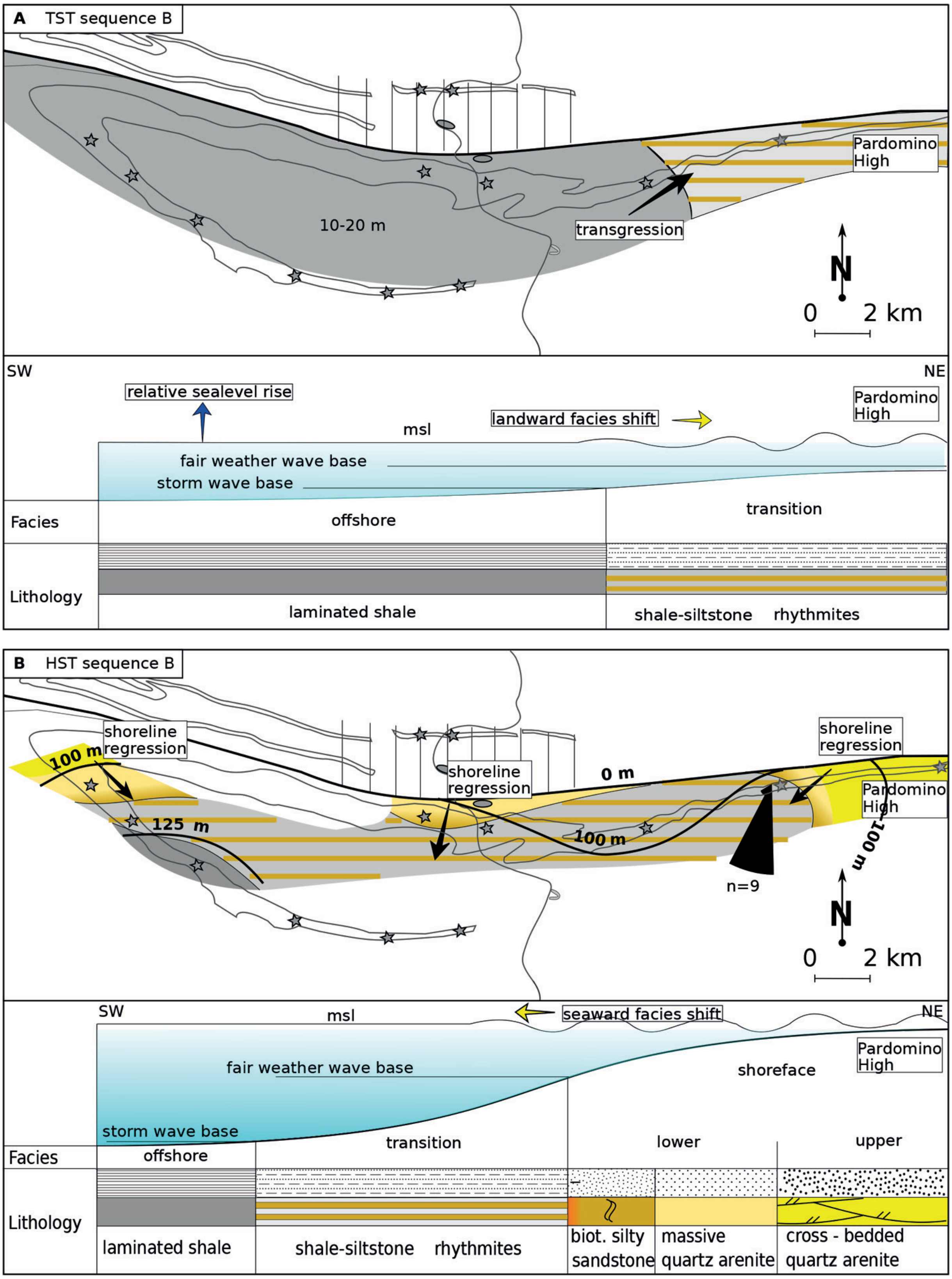

Fig. 19. A – Spatial facies zone reconstruction and depositional profile of the transgressive TST deposits, sequence B; **B** – Spatial facies zone reconstruction and depositional profile of the progradational HST deposits, sequence B. Legend in Table 1 and Fig. 16. TST – transgressive systems tracts; HST – highstand systems tracts; msl – mean sea level; biot. – bioturbated

ditions (Joachimski et al., 2009). The shelf transect of each sequence is subdivided into depositional zones, each with their siliciclastic-carbonate distribution and depositional character. For a general discussion of Upper Devonian palaeogeography, reference is made to Van Loevezijn & Van Loevezijn-Peña (2017). The present paragraph focuses on the Frasnian mixed siliciclastic-carbonate system and the physical mixing of lithologies along depositional dips.

6.1. Mixed inner shelf-siliciclastic outer shelf

The general shelf transect of sequence A displays a low depositional slope profile with gradual transitions and wave-tide processes.

Backshore-upper shoreface zone: As there were no nearby sources, directly sand supply from the land was minor. Fluvial entry points where probably located 50 to 100 km northwest of the study area, where the Upper Devonian is developed in a fluvio-marine environment (Sanchez de la Torre, 1977). Littoral transport by breaking waves and longshore currents delivered large amounts of sand along the shallow-marine coast (Fig. 20) and deposited these in a succession of sand bars, troughs and channels, representing an agitated environment where sediment was reworked by powerful currents. Locally, skeletal echinoderm debris (mainly crinoid ossicles) stabilised the substrate, forming carbonate shoals. Intraclasts, erosion surfaces, coarse bioclastic lag deposits and ferruginous mineralisation surfaces indicate a very turbulent, agitated shoal environment with a low sedimentation rate (Van Loevezijn & Raven, 2017). These shoals represent the shallowest part of the coastal zone. Close to the shoals, wave and tide currents mixed skeletal debris with sand. Away from the shoals towards the lower shoreface, the physical mixing process declined rapidly and the area was gradually colonised by endobenthic communities. Locally, calcareous silty to very fine-grained sands were deposited in a protected, low-energy open lagoonal setting, probably behind bars or barriers of the high-energy shoreface environment.

Lower shoreface zone: In the lower shoreface zone the physical mixing of lithologies was gradually taken over by biogenic mixing. In the upper part of the lower shoreface zone homogenised clean quartz sands were deposited. Closer to the fair-weather wave base silt became gradually admixed and the increased bioturbation resulted in a mottled appearance of the sediment. Locally, the sediments mixed with some carbonates resulting in calcareous sediments.

Transition zone: The transition setting was dominated by the deposition of silts. The sea floor was intensely colonised by endobenthic communities, which almost completely destroyed the primary physical structures and produced homogenised crumbly sandy silt with shale flakes. The ichnofauna and abundant brachiopods, crinoids and solitary coral suggest a nutrient-rich, well-oxygenated envi-

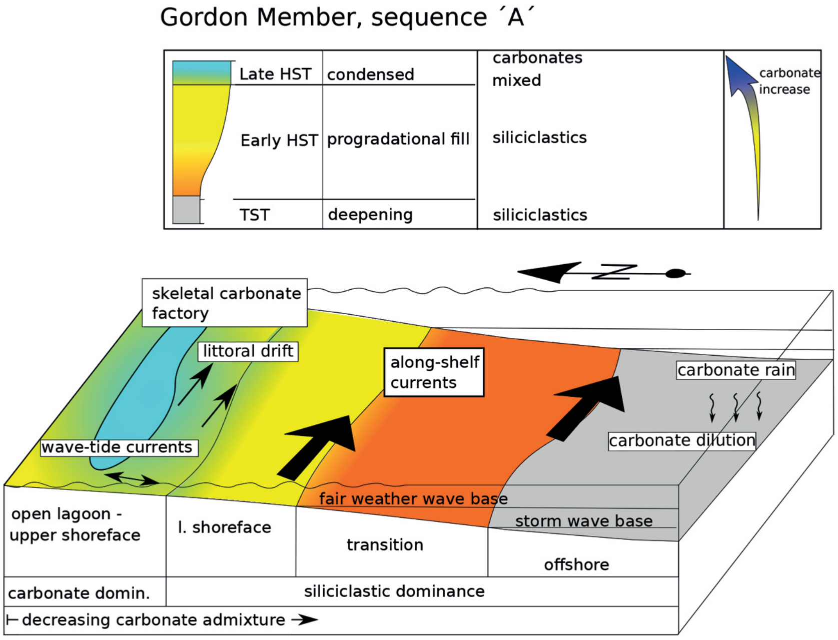

Fig. 20. Model of the shallow-marine mixed system of sequence A, showing the carbonate and siliciclastic distribution and the currents across the depositional profile. Legend in Table 1

ronment, close to fair-weather wave base. Locally, the high water content of the intensely reworded sediment resulted in thixotropic deformation.

Offshore zone: The offshore zone is characterised by persistent deposition of siliciclastic mud. The lack of significant bioturbation indicates reduced oxygen sea bottom levels and/or lack of nutrients (Nichols, 2009), although few horizons with burrows and sparsely distributed brachiopods suggest local benthic activity. Siliciclastic sediment, brought into the coastal area by littoral drift, was distributed by along-shelf currents into the distal parts of the shelf, where the fine-grained sediments settled (Van Loevezijn & Van Loevezijn-Peña, 2017). As these along-shelf currents need sufficient water depth to operate efficiently (Zeller et al., 2015), the coastal progradation forced terrigenous along-shelf distribution far into the offshore direction, diluting pelagic carbonate sedimentation.

6.2. Mixed inner shelf-siliciclastic middle shelf-mixed outer shelf

Sediments of the mixed systems of sequence B were deposited on a steep shelf profile dominated by wave processes of storm-weather and under fair-weather conditions.

Upper shoreface zone: The area was far away from a major siliciclastic sediment source, and the coastal area was fed by littoral drift currents along foreshore and shoreface. The upper shoreface depositional setting was characterised by a turbulent environment with migrating, fine-grained sand bars and troughs. Crinoidal shoals developed locally in the eastern Esla area. The skeletal debris stabilised the constantly shifting siliciclastic sediments of this turbulent environment, thus facilitating coral-stromatoporoid reef development. In this zone an intense mixing of carbonate grains and sand took place. The coarse mixture is absent in transitional and offshore sediments (Fig. 21). Obviously cross-shelf transport was unable to distribute the mixture, and the coarse carbonate-siliciclastic sediments were stored in the shoreface zone. A similar observation was made by Schwartz et al. (2018) for mixed shoreface Hauterivian (Lower Cretaceous) deposits of the Neuquén Basin in Argentina.

Lower shoreface zone: Towards the fair-weather wave base the depositional setting changed from cross-bedded sandstones and limestones to an environment where benthic communities homogenised the sediment, and where primary physical structures were obscured by bioturbation, and with a gradual shift in grain-size to more silty deposits. The lower shoreface deposits are dominat-

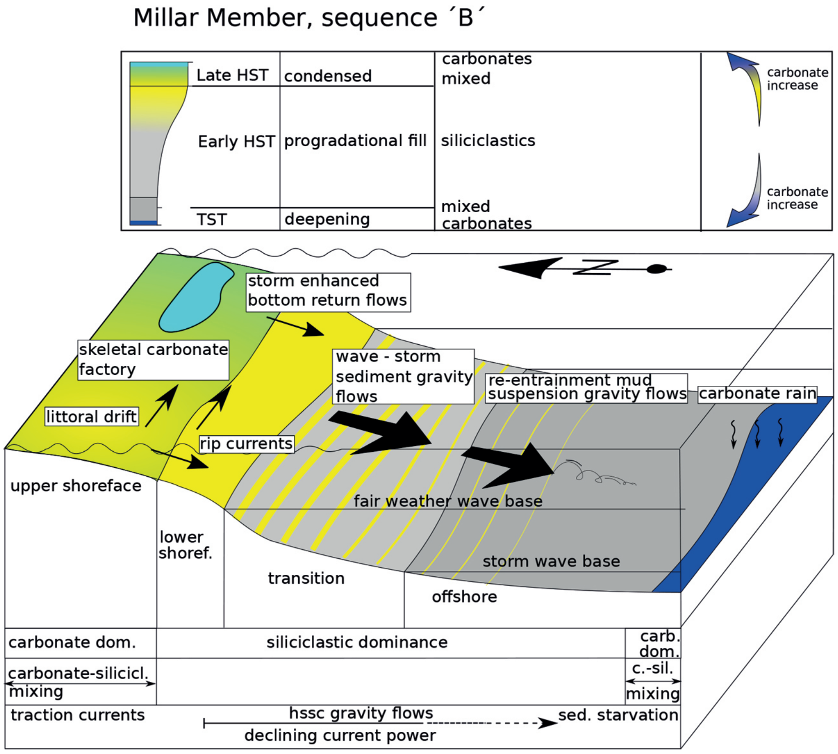

Fig. 21. Model of the shallow-marine mixed system of sequence B, showing the carbonate and siliciclastic distribution and the currents across the depositional profile. Legend in Table 1

ed by siliciclastics with a small amount of skeletal carbonates admixed and are intensely colonised by (endo)benthic communities.

Transition zone: The transitional zone of sequence B is characterised by a profile dominated by storm-weather and fair-weather wave processes exposed in the Matallana section. The succession consists of a tempestite sequence of approximately 100 m organised in coarsening-upward, small-scale cycles of 10 to 30 m (Van Loevezijn & Van Loevezijn-Peña, 2017). The main portion of the tempestite deposits consist of distal tempestites. Upward in one small scale cycle, bed thickness and frequency of tempestites increases, and a cycle is capped by thick-bedded, low-angle swaley cross-stratified shallow channels. Thick proximal tempestites with graded bases and coarse intraclasts, as described by Kumar & Sander (1976), do not occur in the succession. This might be due to the low preservation potential of proximal storm beds, as fair-weather wave action usually erodes older storm beds (Myrow, 1992). Sediments are locally intensely colonised by endobenthic communities and in places completely homogenised beds occur. Most storm beds, however, escaped a complete mixing. The tempestite succession is overlain by bioturbated quartz arenites of the shoreface, and topped by the bar-trough systems of the cross-bedded quartz arenites of the upper shoreface zone. Fairly thick storm bed successions require subsidence of the basin and high rates of sedimentation that preserved the tempestites from reworking by fair-weather waves, tides and subsequent storm erosion (Einsele, 2000, Bádenas et al., 2018). The required subsidence developed during the Frasnian, when a bulge area evolved north of the study area on the inner part of the Cantabrian Zone and downwarping of the surrounding shelf area occurred in the External Zone. Extension of the uplifted source area towards the outer depositional area resulted in a depositional shift in a southerly direction and a steepening of the shelf profile, as is demonstrated in the spatial distribution and vertical facies stack of sequence B. The stronger depositional slope provided an offshore-directed driving force for high suspended sediment concentrations. Cross-shelf transport during peak storm conditions may have been an important factor in the hydrodynamics of sediment distribution (Myrow & Southard, 1996). In this setting storm waves can provide the extra turbulence creating powerful offshore directed gravity flows, transporting the fines deep into the offshore area, facilitated by the steep shelf profile, a process described by Kämpf & Myrow (2014). This resulted in a tempestite succession with a decreasing offshore-directed bed thickness, as a result of the offshore-directed gradual decline of the current power.

Offshore zone: In the outermost offshore area the sedimentation rate was very low. The area was almost completely beyond the reach of the coastal siliciclastic supply by gravity flows. Siliciclastic sediment starvation facilitated the development of a condensed carbonate mud succession out of carbonate rain; the combination of carbonate production in the euphotic zone and the sinking flux out of the surface layer, a process described by, among others, Frank et al. (1999) and recently revised by Berelson et al. (2007). The absence of bioturbation suggests low sea floor oxygen levels (Nichols, 2009). Shoreward, siliciclastic mud prevailed on a well-oxygenated sea floor with locally a rich benthic fauna. In summary, the offshore settings are characterised by an outermost carbonate mud-dominated area poor in oxygen, and with deposition out of suspension, probably from biogenic carbonate rain, a middle mixed carbonate siliciclastic area with a rich benthic fauna of brachiopods and bryozoans, and an inner siliciclastic mud-dominated area where the outermost silty suspension gravity flows were deposited by re-entrainment of sediment by storm waves, a mechanism that can create powerful offshore-directed, sediment-laden, mud-suspension flows, that moves by gravitational forces far into the offshore area on relatively low slopes (Wright et al., 1996; Kämpf & Myrow, 2014).

7. Discussion

Source area: As there is no evidence of direct sediment input from nearby river discharges, siliciclastic sediment was probably delivered to the basin by along-shelf currents and littoral drift. In the northwest and northeast of the study area the Upper Devonian is developed in a fluvio-marine facies (Sanchez de la Torre, 1977), where erosion products of the Asturian geanticline entered the basin, and currents distributed the siliciclastics across the Asturo-Leonese shelf. The different siliciclastic – carbonate distribution patterns of both mixed systems were caused by different sediment distribution processes and by the changing outlines of the Frasnian basin.

Shelf transport: The shallow-marine depositional system of sequence A during TST and early HST conditions was mixed with siliciclastic predominance (Van Loevezijn & Van Loevezijn-Peña, 2017). Coast-parallel currents were responsible for along-shelf detrital sediment distribution. These currents were driven by the available accommodation space on the shelf, and were pushed towards the outermost parts of the shelf, as during the HST the coast prograded basinwards. A late HST carbonate-dominated skeletal shoal environment developed on the inner shelf area, where the water was too shallow for an efficient current to be established. Mixing of the carbonates and siliciclasts was restricted to the shoreface zone. In marked contrast, the siliciclastic-carbonate distribution of sequence B is characterised by two carbonate-dominated belts; a stromatoporoid-coral reef unit in turbulent waters of the shoreface zone and a carbonate mud unit deposited in the deeper offshore zone. In between these areas numerous successive storm events distributed the littoral sands, and built up a rhythmic tempestite shale-sequence in a subsiding basin with a sedimentation rate exceeding downwarping. The resulting HST sequence coarsens and thickens upwards, grading from shelf muds, thin-bedded tempestites, thick-bedded tempestites, to the coastal sand environment and skeletal reef deposits of the shoreface. Basinward gravity-flow power, responsible for the cross-shelf siliciclastic distribution, decreased, resulting in a distal thinning of the tempestites. Downdip such a depositional setting a gradual decrease of siliciclastic deposition occurs (Myrow, 1992). In the outermost part of the shelf a condensed, sediment-starved environment existed. There carbonate sedimentation was not diluted by siliciclasts and a carbonate mud succession was formed out of suspension. This result corresponds with the case studies of mixed systems in Schwartz et al. (2018). Dominant marine transport processes can create a variety of mixed systems, where along-shelf currents often display carbonate predominance in the proximal shelf zone, and an increase of siliciclastics admixed in the distal parts, whereas offshore-directed, storm-related cross-shelf flows often display proximal siliciclastic predominance and mixed carbonate-siliciclastics in the distal shelf zones.

Tectonics: Tectonics, induced by the approaching Variscan orogenic front, probably played an important role in relative sea level, as well as the changing shape of the Frasnian basin. The Upper Devonian sediments were deposited during the initial phase of the Variscan orogeny, with a gradual uplift of the Asturian geanticline and the Pardomino High to the north and east, and subsidence in the External Zone to the south and west (Van Loevezijn & Van Loevezijn-Peña, 2017), which shaped basin geometry during deposition (Fig. 2). Therefore, Upper Devonian stratal architectures have some characteristics that are closely similar to syntectonic strata features as described by Ford (2004), with wedging, truncation and onlap. Initially, the Frasnian basin had a very gentle depositional slope as is demonstrated in the facies maps of sequence A. In the course of the Frasnian uplift of the inner area of the Cantabrian Zone and downwarping of the depositional area in the External Zone gradually shaped the basin, and the depositional area shifted basinwards. At the end of the Frasnian, a shelf with a steep depositional dip (Van Loevezijn, 1989) formed at the outermost edge of the Cantabrian Zone with shoal and reef areas in the shoreface zone, tempestite-shale succession in the transition zone and carbonate muds in the outermost offshore area.

8. Conclusions

The approach of the Variscan orogenic front changed the Asturo-Leonese basin geometry dur-

Table 2. Identification of basin scale factors and depositional processes of both Frasnian siliciclastic-carbonate systems

Lithological unit	Age	Sequence	Depositional setting	Climate	Tectonics	Detrital source	Shelf transport	Carbonate production	Facies belt
Gordón Mbr.	Frasn.	3rd order	Shallow marine non-rimmed shelf, gentle slope	Greenhouse	Early stage foreland basin	Litoral drift	Along-shelf currents	Turbid shallow water	Shf.: M/C Trans.: S Offsh.: S
Millar Mbr.	Frasn.	3rd order	Shallow marine non-rimmed shelf, steep slope	Greenhouse	Early stage foreland basin	Litoral drift	Storm related down-dip currents	Turbid shallow water, distal deep water	Shf.: M/C Trans.: S Offsh.: M/C

Shf. – shoreface, Trans. – transition, Offsh. – offshore, S – siliciclastic, C – carbonate, M – mixed.

ing the Frasnian. Therefore, the Upper Devonian stratal architectures have some characteristics that are closely similar to syntectonic strata features, with wedging, truncation and onlap.

Frasnian detrital sediment supply from the Asturian geanticline entered the basin outside the study area, and was delivered by along-shelf currents, storm-related down-dip currents, and by littoral transport in the foreshore and shoreface zones.

Frasnian siliciclastic-carbonate mixing was mainly a function of basin geometry, availability of sand and the way sediment was distributed by the shelf currents.

Siliciclastic distribution by along-shelf currents was driven by the relative sea level and the available accommodation space on the shelf. In these settings, siliciclastics dilute distal carbonate sedimentation (sequence A). In marked contrast, siliciclastic distribution by sediment gravity flows generated by wave-storm activity, tend to decrease basinwards, giving way to a condensed distal carbonate development (sequence B) (Table 2).

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