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Frasnian (Upper Devonian) lithostratigraphy of the Bernesga Valley (Cantabrian Mountains, NW Spain)

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Abstract

Sequence stratigraphic units are defined in terms of changes in relative sea level, and not on the compositional similarity of the lithology of the rock units. Sequence boundaries were used to support the formal definitions of the Gordón Member and the Millar Member of the Frasnian Nocedo Formation (Cantabrian Mountains). Therefore, each member consists of a broad range of lithologies. In this study each sequence of the Nocedo Formation is subdivided into formal lithological units and from each unit the stratigraphic characteristics and spatial distribution pattern is presented. Within one sequence the lithological units have gradational contacts, and their lateral distribution is consistent and complementary, allowing the understanding of the palaeogeographic picture of the region.

Keywords: Nocedo Formation, Cantabrian Mountains, sequence boundaries, sedimentology

1. Introduction

The Cantabrian Mountains of Northern Spain contain a well-preserved Palaeozoic sedimentary succession. The Bernesga valley is the classic Devonian area, where almost all the type sections of the Devonian formations and members of the southern Cantabrian Mountains were defined (Comte, 1959). They occur mainly in two large structures; the Alba syncline and the Pedroso Syncline (Fig. 1).

The Upper Devonian succession in this area is subdivided into three formations; the sandstones of the Nocedo Formation of Frasnian age, the shales of the Fueyo Formation of early Famennian age, and the sandstones of the Ermita Formation of Famennian age locally reaching into the Carboniferous (Tournaisian) (Aramburu et al., 2004). Although each formation is characterized by a dominant lithology, considerable amounts of sand, shale, silt and carbonates are intercalated and/or admixed. In contrast with the Lower and Middle Devonian successions, these Upper Devonian units vary considerably over short distances in (litho) facies and thickness. The scarcity of fossils and large lithological variations hamper (and often preclude) conclusive correlations of the different lithologies. Sequence stratigraphy can help to resolve the correlation problem, allowing the introduction of cycles based on a sedimentological and sequence stratigraphical framework, and the use of this as a correlation tool. The correlatable sequence stratigraphical surfaces (sequence boundaries, transgressive surfaces, maximum flooding surfaces) introduce a framework, allowing the understanding of genetic relations between the different lithologies, and the palaeogeographic evolution through time. It is a useful alternative to the lithostratigraphic approach, which is based on the similarity of the lithology of rock units rather than timelines. A sequence stratigraphic model for the Upper Devonian mixed siliciclas-

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tic-carbonate succession of the southern Cantabrian Mountains was introduced by Van Loevezijn & Van Loevezijn Peña (2017), which correlates the sequences with their transgressive and regressive genetically related lithologies: sequence A (Nocedo Formation, Gordón Member), sequence B (Nocedo Formation, Millar Member) and sequence C (Fueyo Formation and lower part Ermita Formation). The present study focuses on the Gordón Member and Millar Member of the Nocedo Formation of the Bernesga area, in the southernmost outcrops of the Cantabrian Mountains. In this study these members are subdivided into formal lithological units and their stratigraphic characteristics and spatial distribution patterns are presented.

2. Methodology

The present study is an investigation on the stratigraphy of the Upper Devonian rocks in the southern Cantabrian Mountains as part of the Devonian project of the former Department of Palaeontology and Stratigraphy, University of Leiden, the Netherlands. The Upper Devonian investigation has three main objectives: 1) Analise the Upper Devonian sedimentary (and sequence stratigraphic) successions in the southern slope of the Cantabrian Mountains between the rivers Esla in the east and the river Sil in the west. 2) Evaluate depositional environments of the sections using a combination of field observations, detailed microscope work and fossil analysis. 3) Compile an Upper Devonian palaeogeographic history of the southern Cantabrian Mountains. Field observations and measured sections were worked out in detail including recognition of facies types. Rock samples and fossils were studied in the laboratory, including the preparation and study of thin sections and the extraction and study of conodonts, which were used to control the correlations based on lithology. The Upper Devonian deposits of the Nocedo Formation in the Bernesga area were studied in fourteen sections; twelve in the Alba syncline, and two in the Pedroso syncline.

3. Geological setting

The Cantabrian Zone contains two Devonian facies; The pelagic Palencian facies in the east, and the Asturo-Leonese facies in the south and west. The Palencian facies area is considered allochthonous representing the deeper southwestern continuation of the Asturo-Leonese facies (Frankenfeld, 1984). The latter is characterised by a shallow-marine shelf succession, with a systematic change towards more

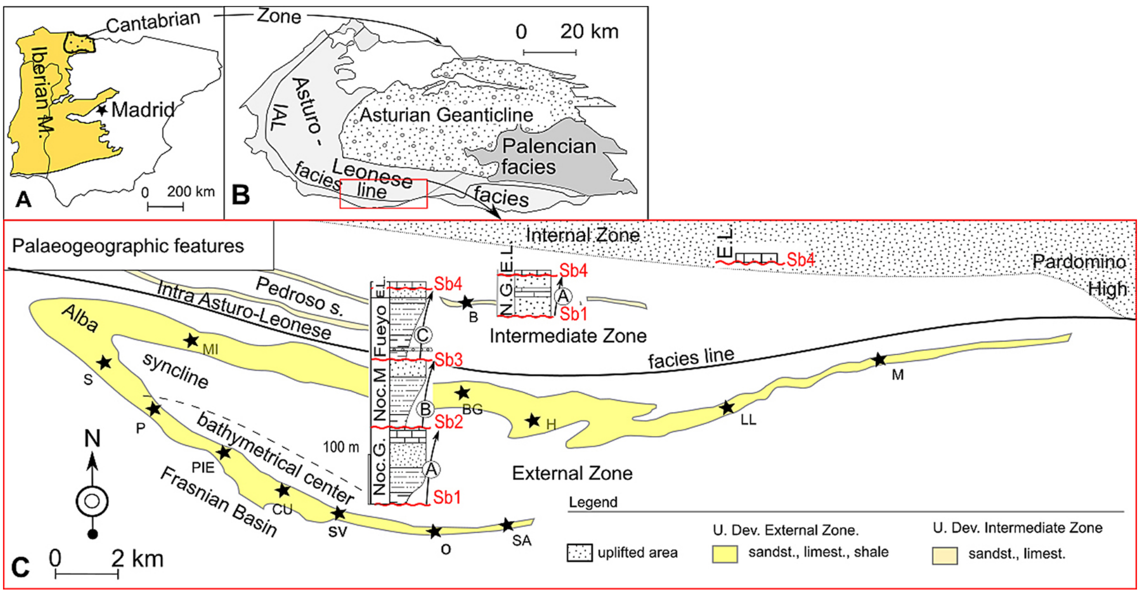

Fig. 1. Location of the Cantabrian Zone and study area in NW Spain. **A** – Situation map of the Iberian Peninsula with the Iberian Massif and the Cantabrian Zone; **B** – Schematic geological map showing the major Cantabrian palaeogeographic units; **C** – Map of the study area with the location of sections and areas mentioned in the text; Noc. G. – Nocedo Formation Gordón Member, Noc. M. – Nocedo Formation Millar Member, E.L. – Ermita Formation, L. – Ermita Formation Llombera Beds, M – Matallana, LL – Llombera, H – Huergas, BG – Barrios de Gordón, MI – Mirantes de Luna, S – Saguera, P – Portilla, PIE – Piedrasecha, Cu – Cuevas, SV – Santiago de las Villas, O – Olleros de Alba, SA – Sorribos de Alba, B – Beberino.

distal depositional environments and more continuous successions from the core of the Cantabrian Zone towards the outer parts of the facies area (Fig. 1C). The spatial distribution of the Upper Devonian successions divides the Asturo-Leonese facies area into three zones: the External-, Intermediate-, and Internal facies zones (Van Loevezijn, 1986). They occur in longitudinal belts parallel to the curved Variscan Asturian Oroclinal structure. 'Unfolding' of the structure reveal that the facies zones run parallel to a north-south palaeo-coastline in current geographic coordinates, with the land area of the uplifted core area of the Cantabrian Zone, the Asturian Geanticline or Ebro Massif, where Devonian strata are lacking, in the east (Keller et al., 2007; Weil et al., 2013). The study area is located in the External Zone of the southernmost part of the Asturo-Leonese facies area.

4. Sequences and lithostratigraphic units

Sequences are not lithostratigraphic units since they are defined in terms of changes in relative sea level, not based on the compositional similarity of the lithology of the rock units. The Gordón and Millar members of the Nocedo Formation are both based on a sequence stratigraphic approach (the sequences A and B respectively (Fig. 1C), separated by sequence boundaries (sb1 to sb4) and with the maximum flooding bounding surfaces (mfs) between the transgressive and regressive tracts (Van Loevezijn & Van Loevezijn Peña, 2017). The Gordón Member (sequence A) has a thickness that varies from about 70 to about 300 m. The Millar Member (sequence B) varies from about 70 to about 120 m. Each sequence consists of a broad range of different, genetical related, lithologies; the Gordón Member consists, from base to top, of a shale unit, a siltstone unit, a sandstone unit, the Molino Limestone, and an overlying calcareous siltstone-sandstone unit (see paragraph 4) (Fig. 2A). The Millar Member consists of a basal shale unit, an overlying sandstone-shale unit, and a sandstone unit (see paragraph 5) (Fig. 2B). Going from member smaller in the hierarchy of lithostratigraphic rank, these sub-member units are beds. For each bed in the Bernesga area a short lithological characterisation will be given (for a more detailed sedimentological description of the lithologies, the reader is referred to Van Loevezijn & Van Loevezijn Peña (2017), Van Loevezijn & Raven (2017, 2020, 2021), and García López & Sanz López (2002)). Type sections will be appointed, the vertical and spatial distributions discussed, and formal names will be introduced. The locations of the chosen type sections were determined by accessibility of the site, exposure, thickness, and completeness of the succession. However, it should be noted that caution should be exercised when introducing new names; they should be proposed only when there is a clear need for them. Every geologist, before taking steps to establish and name a new unit, should carefully examine whether adding another name will in fact improve the understanding of the geol-

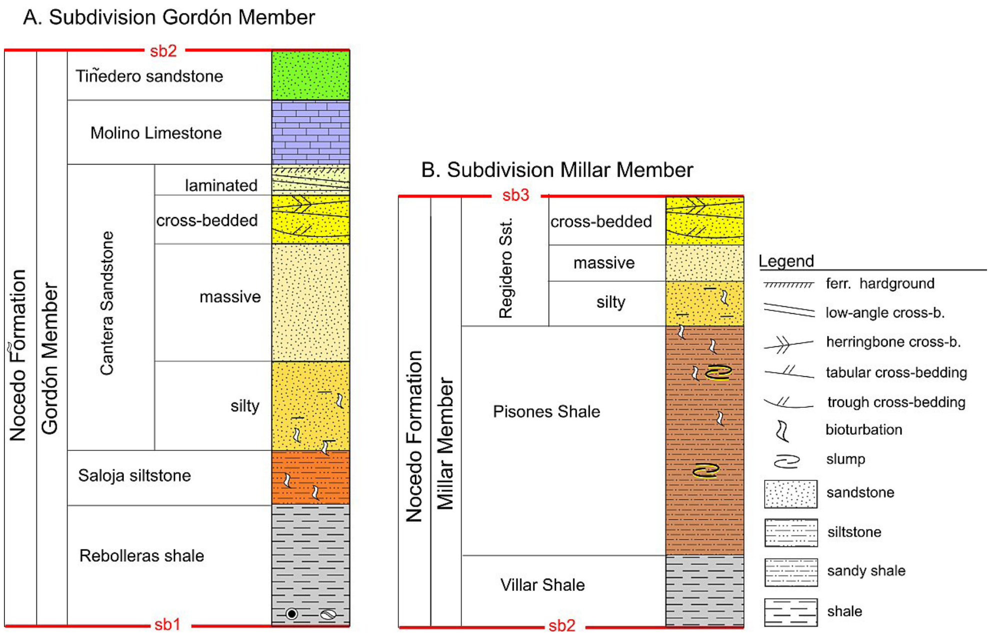

Fig. 2. Subdivision of the Nocedo Formation. **A –** Lithologocal subdivision of the Gordón Member. Molino Limestone Bed after García-López & Sanz-López (2002); **B –** Lithological subdivision of the Millar Member.

ogy (Staines, 1985). Because of the complex Upper Devonian lithology in the Cantabrian Zone, with large lithological variations over short distances, an urgent need for well-defined lithological units exists to define stratigraphic positions and locations of fossils and facies, to bring more order and precision into the Upper Devonian stratigraphy, and finally, to improve geological communication.

5. Nocedo Formation, Gordón Member

The Gordón Member occurs in the External and Intermediate areas of the Cantabrian Zone, (Fig. 1) (Van Loevezijn, 2024). In the External Zone it is sandwiched between the underlying limestones of the Portilla Formation, and the overlying Millar Member of the Nocedo Formation. In the Intermediate Zone the shale and siltstone intercalations in the lower half of the Gordón Member are absent, and the unit consists of a thin sandy succession, overlain by the transgressive Llombera Beds of late Famennian-Tournaisian age. The member consists of five lithological units. García López & Sanz López (2002) introduced the Molino Limestone. For the remaining units a name is here introduced, from base to top the Rebolleras Shale, the Saloja Siltstone, the Cantera Sandstone, and the Tiñedero Sandstone. The Molino Limestone is situated between the Cantera Sandstone and Tiñedero Sandstone (Fig. 2B). These units constitute one depositional cycle, bounded by sequence boundaries sb1(lower bounding surface) and sb2 or sb4 (upper bounding surface). The units are genetically related and fit into one depositional model. They can be correlated, at least in part, with biostratigraphy, which, for discontinuous outcrops and facies variations become critical.

5.1. Gordón Member; Rebolleras Shale Bed

Name, type section, and extension: The shale unit is named after the Rebolleras Valley near Barrios de Gordón. The type section is located 1 km southwest of the village Barrios de Gordón (Barrios Abajo), along the east side of the mountain trail from Barrios to Piedrasecha, in the narrow valley of the Arroyo de Rebolleras (lat.: 42°50′39″, long.: –5°42′14″). It is an excellent exposure with good accessibility (Fig. 3). The Rebolleras Shale occurs in the outer part of the External Zone of the Asturo-Leonese facies area (Figs 1, 4A). Thickness varies between 10 and 38 m, with a gradual thickness decrease towards the Intermediate Zone in the north. In the eastern half of the study area, towards the Pardomino High, the shales do not occur. In the section above the village Mirantes de Luna in the nose of the Alba syncline, a 10.5 m thick, well exposed, Rebolleras Shale succession occurs (lat.: 42°52′4″ lon.: –5°50′4″). Well exposed sections also occur in the valleys of the villages Sagüera de Luna (22 m) and Piedrasecha (38 m). The unit is partly exposed in the valley of Portilla de Luna (36 m).

Boundaries: The unit is bounded by the underlying limestones of the Portilla Formation and the overlying succession of the Saloja Siltstone (Fig. 5). Both bounding surfaces are well exposed at the type section of Barrios de Gordón. The lower boundary is often a sharp, clearly erosive surface (sequence boundary 1 of Van Loevezijn & Van Loevezijn Peña 2017); the upper boundary is in most sections a gradual contact with the overlying siltstone succession. In the Mirantes de Luna section however, an abrupt contact with the overlying Cantera Sandstone occurs.

Lithologic description: Grey-brown calcareous laminated shales. Locally burrowed and poor in

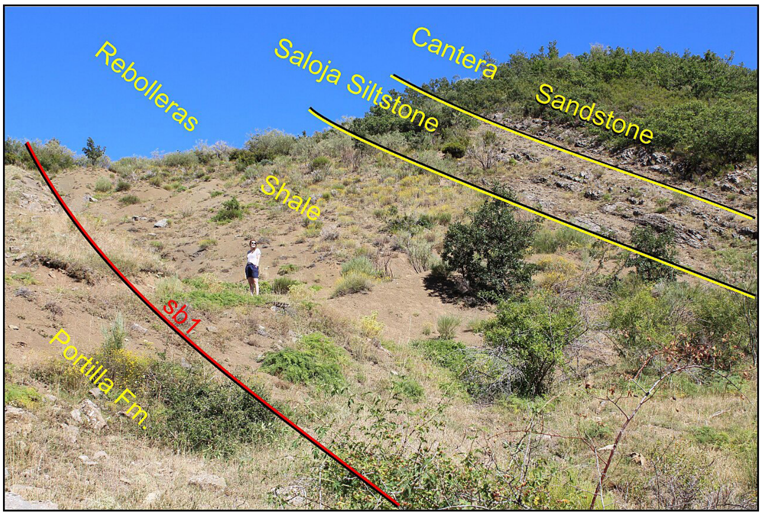

Fig. 3. Type section of the Rebolleras Shale in the arroyo de Rebolleras south of Barrios de Gordón, with the gradual transitions between Rebolleras Shale, Saloja Siltstone, and Cantera Sandstone. For location of sections see Figure 1.

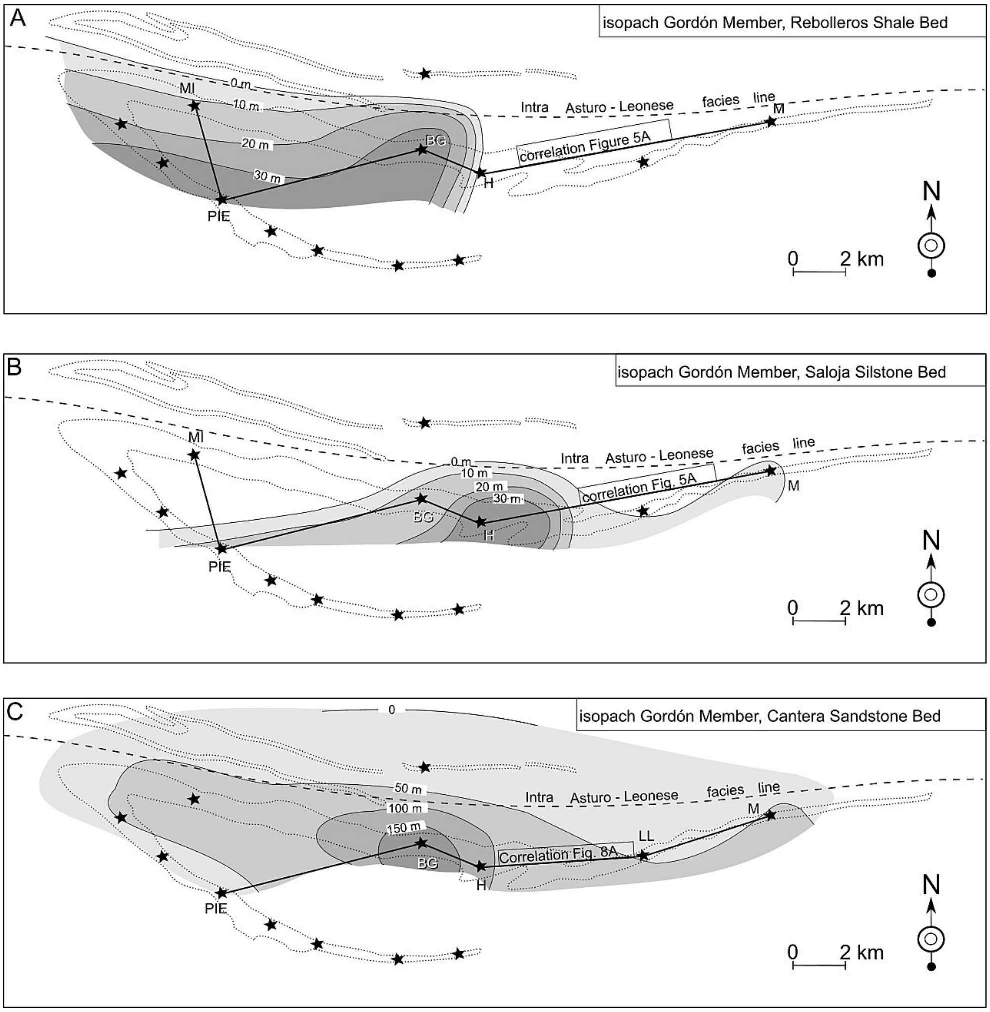

Fig. 4. Isopach patterns. **A** – Isopach pattern of the Rebolleros Shale Bed based on the thicknesses measured in the different sections. Backround map and section names as Fig. 1C. Stratigraphic correlation of Fig. 5A indicated by the connection line between the sections; **B** – Isopach pattern of the Saloja Siltstone Bed based on the thicknesses measured in the different sections. Backround map and section names as Fig. 1C. Stratigraphic correlation of Fig. 5A indicated by the connection line between the sections; **C** – Isopach pattern of the Cantera Sandstone Bed based on the thicknesses measured in the different sections. Backround map and section names as Fig. 1C. Stratigraphic correlation of Fig. 8A indicated by the connection line between the sections.

fossils. In the lower 5 m some calcareous, ferruginous, mud concretions occur with thin shelled small fossils: brachiopods, trilobites, tentaculites, bivalves and conodonts.

Biostratigraphy: The uppermost part of the reef deposits of the Portilla Formation contains conodonts from the Late Givetian *hermanni-cristatus* Zone (García López & Sanz López, 2002). This is confirmed by the presence of the conodonts *Polygnathus decorosus, P. dubius, Belodella* sp., *Icriodus difficilis,* and *I. eslaensis* in sample BGC1 from the top of the Portilla Formation at Barrios de Gordón (Van Loevezijn, 1988). At Piedrasecha the section is affected by by faults. Sample PIEC7 from this section, located in a limestone succession 6.5 m below the base of the Rebolleras Shale Bed, contains *Icriodus corniger corniger,* indicating the Upper Emsian-Lower Eifelian, and correlates with the Lower-Middle Devonian Santa Lucía Formation. Sample PIEC6, located 0.5 m below the Rebolleras Shale Bed, contains *Polygnathus linguiformis linguiformis* (delta), *P. linguiformis linguiformis* (gamma), *P. dubius, Icriodus dificilis,* and *I. obliquimarginatus* indicating the Middle *varcus* Subzone, and correlates with the Middle Devonian Portilla Formation (Van Loevezijn, 1988). Due to complicated thrusting and tectonic erosion (see Rodrígez Fernandez et al., 1985), the thickness of these formations was reduced substantially. The basal part of the overlying Rebolleras shales, contains concretions with small fossils of the bivalve *Buchiola* and the tentaculite *Striatostiliolina striata*. In calcareous burrowed nodules at

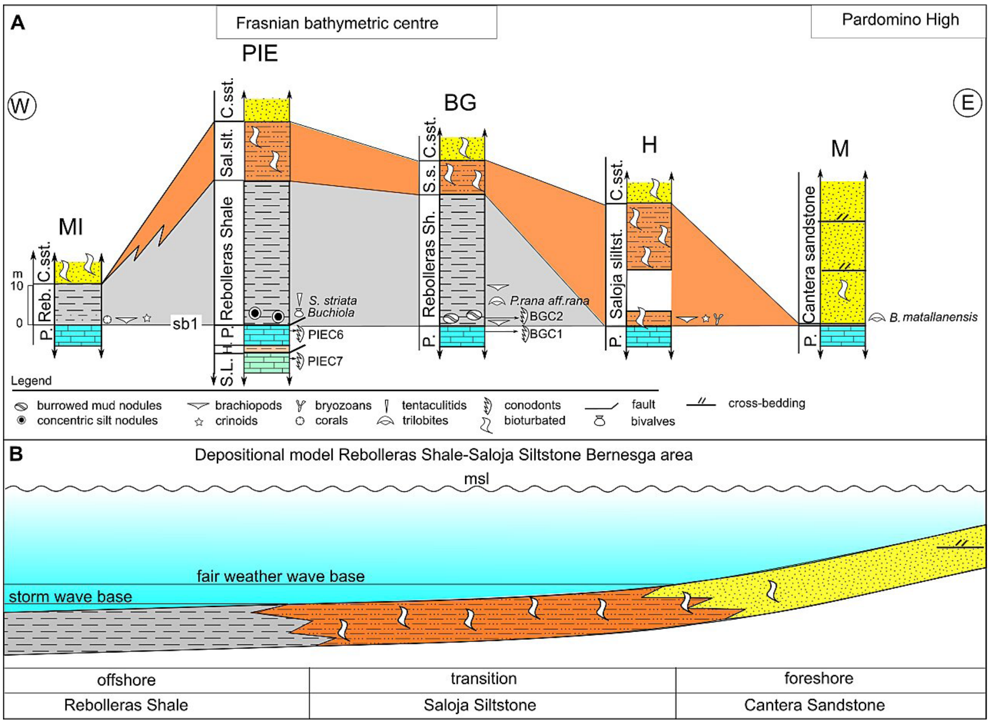

Fig. 5. Lithostratigraphic correlation and sedimentation model of the Rebolleras Shale and Saloja Siltstone. **A** – East-West correlation of the Rebolleras Shale and the Saloja Siltstone; **B** – Sedimentation scheme for the Rebolleras Shale and Saloja Siltstone; S.L . – Santa Lucía Formation, H. – Huergas Formation, P. – Portilla Formation, S. – Saloja Shale, C. – Cantera Sandstone. For location of sections see Figure 1.

the base of the Rebolleras shales of section Barrios de Gordón large quantities of the trilobite *Phacops rana* aff. *rana* and the conodonts *Polygnathus decorosus* and *Icriodus symmetricus* occur (sample BGC2 in Van Loevezijn, 1988). The age of the base of the Gordón Member has not yet been well established, and the Rebolleras Shale may include the Givetian/Frasnian boundary.

Interpretation: The Rebolleras shales constitute the basal part of the Gordón Member and rest with a sharp contact on the limestones of the Portilla Formation. They occur southwest of the section Huergas de Gordón in the outermost part of the External Zone, and represent the most distal, depositional area of the basin, below storm wave base, where only the finest sediment settled down from suspension (Reineck & Singh, 1975; Nichols, 2009). In the central part of the basin these deposits are replaced by bioturbated siltstones.

5.2. Gordón Member; Saloja Siltstone Bed

Name, type section, and extension: The siltsone is here named after a hill slope near the type section at Huergas de Gordón. The type section is located just south of the village Huergas de Gordón along the east side of N630 road to León (lat.: 42°50′24″ lon.: –5°39′18″). The Saloja Siltstone occurs in the External Zone of the Asturo-Leonese facies area (Figs 1, 4B). The general thickness ranges between 8–33 m.

In the western part of the study area, e.g. in the Mirantes de Luna section, the unit is absent. Eastward, near Barrios de Gordón, a thin Saloja Siltstone succession occurs (8 m) (Fig. 5A), which rapidly increases to more than 30 m in the type section of Huergas de Gordón. Further eastward the unit is very thin or absent, and the easternmost section of Matallana contains a succession of only few cm of orange siltstone.

Lithologic description: Grey brown nodular, highly bioturbated, calcareous siltstones, with an argillaceous basal part and up-section admixed with very fine-grained sandstone. In the basal part, close to the limestones of the underlying Portilla Formation, abundant brachiopods, bryozoans and crinoid ossicles occur.

Boundaries: Lower bounding surface is a gradual contact with the underlying Rebolleras Shale. In the eastern part of the Bernesga area, where the shales are absent, the siltstone unit rests with a sharp contact on the Portilla Formation (Fig. 6). The upper bounding surface is a gradual contact with the overlying sandstone succession (Fig. 5).

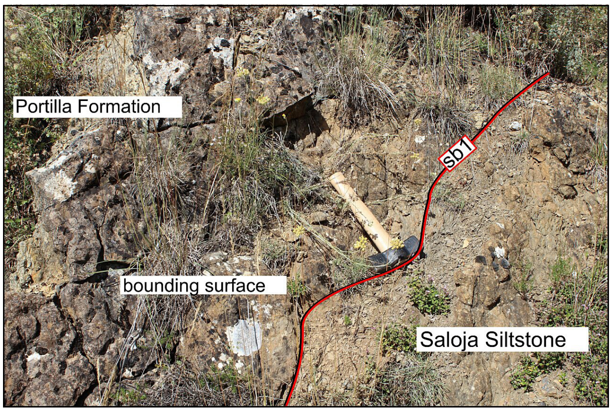

Fig. 6. Sharp, erosive bounding surface sb1, separating the Portilla Formation from the overlying Saloja Siltstone of the Nocedo Formation, section Huergas de Gordón. For location of sections see Figure 1.

Biostratigraphy: An uppermost Givetian conodont fauna is found in the topmost part of the underlying Portilla Formation at Huergas de Gordón (see above), and a lower Frasnian conodont fauna occurs up-section, in the base of the Molino Limestone (García López & Sanz López, 2002). which probably places the age of Saloja Siltstone close to the Givetian-Frasnian boundary.

Interpretation: The siltstone succession is well developed in the central part of the basin, with a thickness up to 33 m, and is replaced by sandstones in the more proximal sections of the basin towards the northeast. The very bioturbated nodular sediment represents low bottom energy conditions with a regular supply of sand and silt. The intense colonisation of benthic communities indicates well oxygenated sea floor conditions, probably the transitional zone between fair weather and storm weather wave base (Reineck & Singh, 1975; Nichols, 2009).

5.3. Gordón Member; Cantera Sandstone Bed

Name, type section and extension: The Cantera Sandstone is named after a 'cantera' (open cast mine in Spanish) in the type section, where the sandstone was excavated. The type locality of the Cantera Sandstone is located in section Huergas de Gordón, just south of the village Huergas de Gordón along the east side of N630 road to León (section H, 112 m thick) (lat.: 42°50′20″ lon.: –5°39′20″). Another, very well exposed, section occurs in the valley of Matallana de Torío, where the thickness is reduced to 55 m (lat.: 42°51′5″ lon.: –5°31′22″). The sandstone extends into the Intermediate and External Zones of the Asturo-Leonese facies area (Figs 1, 4C), and has a general thickness between 35 and 55 m, with exceptional thick developments of 110 – 150 m near the sections of Huergas and Barrios.

Lithologic description: A complete developed sandstone succession consists from bottom to top of grey-brown bioturbated silty, very-fine grained quartz sandstone (Fig. 7A), grey-brown massive bioturbated very-fine grained quartz sandstone (Fig. 7B), light-yellow cross-bedded very-fine to fine grained quartz sandstone, and laminated low-an-

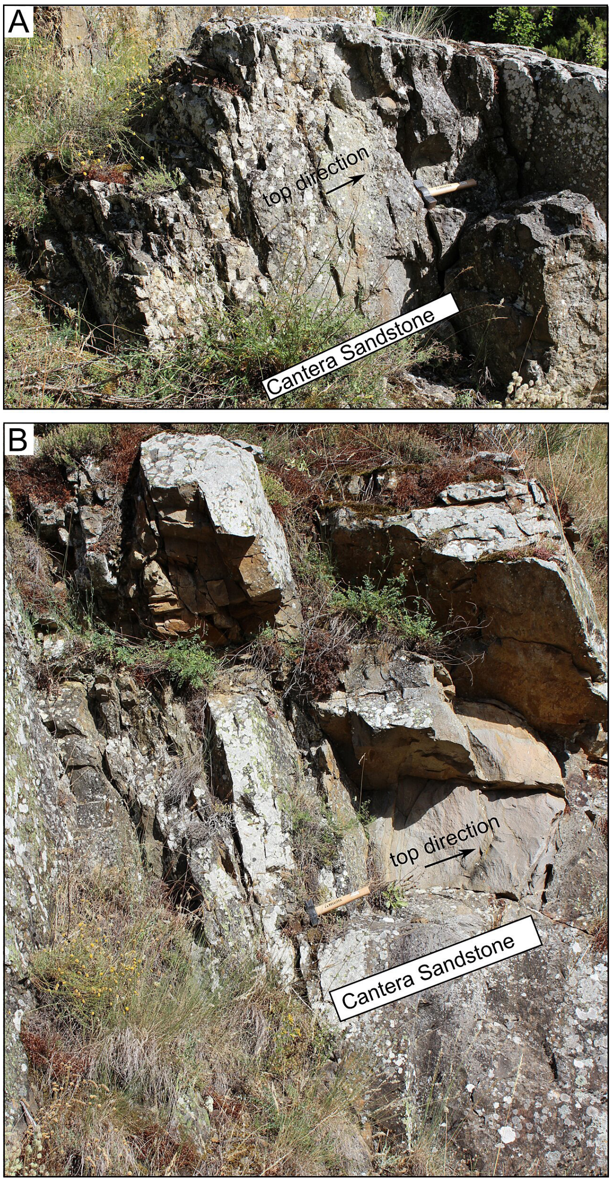

Fig. 7. Cantera Sandstone Bed lithofacies. **A** – Wave-ripple laminated, bioturbated, nodular, silty standstone of the silty sandstone facies of the Cantera Sandstone, section Huergas de Gordón. For location of sections see Figure 1; **B** – The massive sandstone facies of the Cantera Sandstone, typesection south of Huergas de Gordón. For location of sections see Figure 1.

gle cross-bedded very-fine to fine grained quartz sandstone with ferruginous mineralisation surfaces and muddy ripple laminated intercalations (Fig. 8). The fauna consists mainly of brachiopods and small amounts of crinoid ossicles, and few trilobites.

Boundaries: The Cantera Sandstone is underlain by the Saloja Siltsone. In the eastern and northern parts of the Bernesga area the Saloja Siltstone is absent and the sandstone unit rests with a sharp, erosive contact on the limestones of the Portilla Formation. The unit is overlain by the sandy limestones of the Molino Limestone. Where the Molino limestone is absent, the sandstones are overlain by the shales of the Millar Member, separated by bounding surface sb2.

Biostratigraphy:. In the basal part of the Cantera Sandstone in the Matallana section the trilobite *Bradocrypaeus matallanensis* occurs (Smeenk, 1983) indicating the Frasnian. Conodonts from the top of the underlying Portilla Formation correlate with the upper part of the *Sch.hermanni–P.cristatus* Zone, late Givetian in age, and a conodont fauna from the basal part of the overlying Molino Limestone correlates with the Upper *M. falsiovalis* Zone, early Frasnian (García López & Sanz López, 2002). The Cantera Sandstone in between probably correlates with the lower Frasnian.

Interpretation: The Cantera Sandstone represents the sandy coastal area from the lower shoreface zone (silty bioturbated sandstone and massive sandstone), the upper shoreface zone (cross-bedded sandstone) to foreshore (low angle cross-laminated sandstones). The thickest sandstone successions occur in the central part of the basin, near the sections Barrios de Gordón and Huergas the Gordón with silty sandstone and massive sandstone successions of the lower shoreface, overlain by the cross-bedded sandstones of the upper shoreface. Towards the

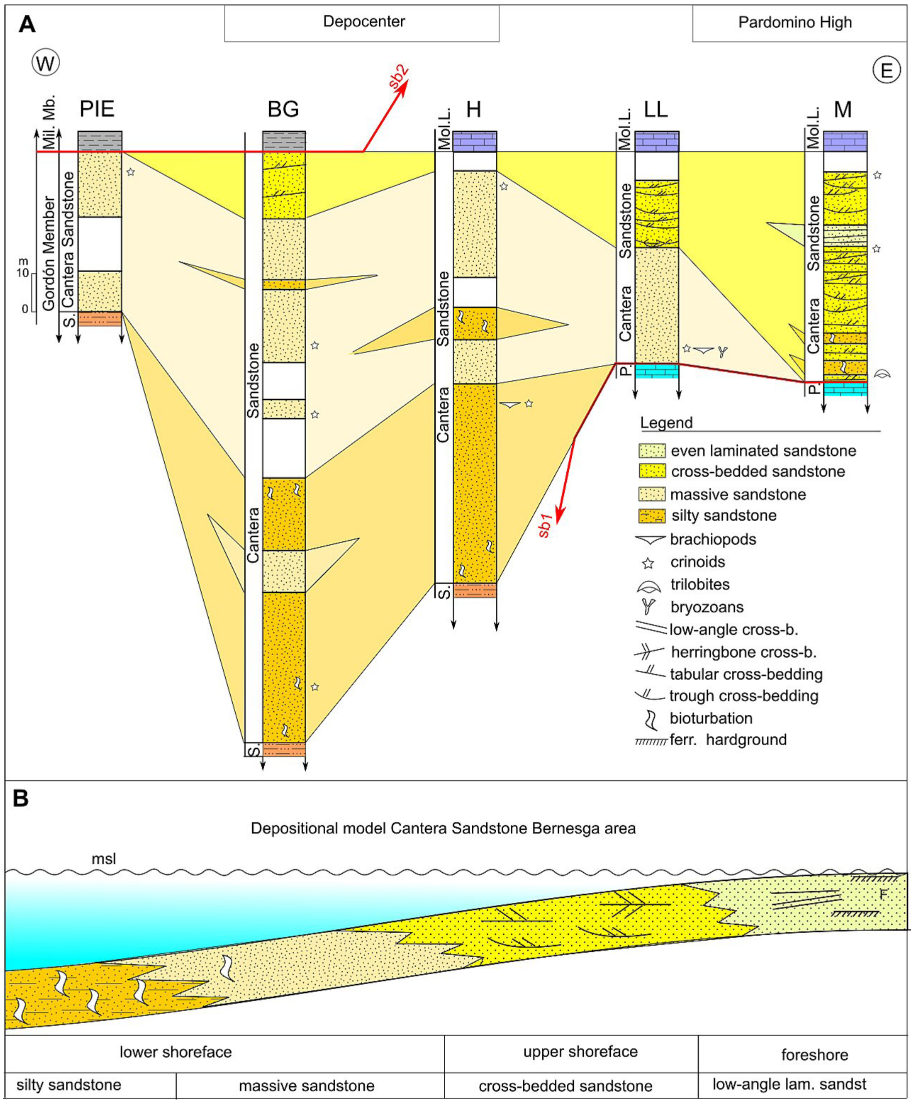

Fig. 8. Lithostratigraphic correlation and sedimentation model of the Cantera Sandstone. **A** – East-west corelation scheme of the Cantera Sandstone; **B** – Depositional model Cantera Sandstone. For location of sections see Figure 1.

southwest, the distal, part of the basin, a thin succession of lower shoreface sandstone occurs, while towards the northeastern, the proximal, part of the basin, a thin succession of ferruginous cross-bedded sandstone with low-angle laminated sandstone intercalations occur.

5.4. Gordón Member; Molino Limestone Bed

Name, type section and extension: The name 'Molino Limestone' was introduced by García Lopez & Sanz-Lopez (2002) for the 52 m thick limestone lens in the top of the Gordón Member exposed in a bend of the N630 road to León, just south of Huergas de Gordón, about 140 m above the base of the Nocedo Formation (section Huergas de Gordón: lat.: 42°50′17″ lon.: –5°39′21″). The limestone was stratigraphically analysed by Van Loevezijn & Raven (2017). The limestone occurs in the External and Intermediate Zones of the Asturo-Leonese facies area. The limestone disappears within 1 km west of the type section, and occurs to the southwest as laterally discontinuous cross-bedded, sandy, limestone lenses above the Cantera Sandstone near Olleros de Alba (section O), Portilla de Luna (section P), and Sagüera (section S). The thickest limestone developments are located in the central and eastern parts, away from the bathymetrical centre in the southwest, in the sections Huergas de Gordón, Llombera, and Matallana (20–55 m thick). Northwards, it occurs in the sections at Beberino and Vega de Gordón (Figs. 1, 9A).

Boundaries: The Molino Limestone is underlain by the Cantera Sandstone. However, the lower boundary in the Bernesga area is not well exposed. The unit is overlain by the calcareous shales, siltstones, and sandstones of the Tiñedero Sandstone, or by the Villar Shale of the Millar Member.

Lithologic description: In the Bernesga area four Molino facies types occur: wackestones and packsones with siltstone intercalations, cross-bedded sandy grainstones, fine-grained bioclastic grainstones, and coarse-grained, ferruginous, bioclastic grainstones with debris intercalations of bioclastic lags, and erosion surfaces (Figs 10, 11).

Biostratigraphy: The Molino Limestone contains rich conodont faunas (Raven, 1983; García-Lopez, 1987; García-Lopez & Sanz-Lopez, 2003 amongst others). García-Lopez & Sanz-Lopez (2003) correlated the Molino conodont faunas with the Upper *M. falsiovalis* Zone, the *Pa. transitans* Zone, the *Pa.*

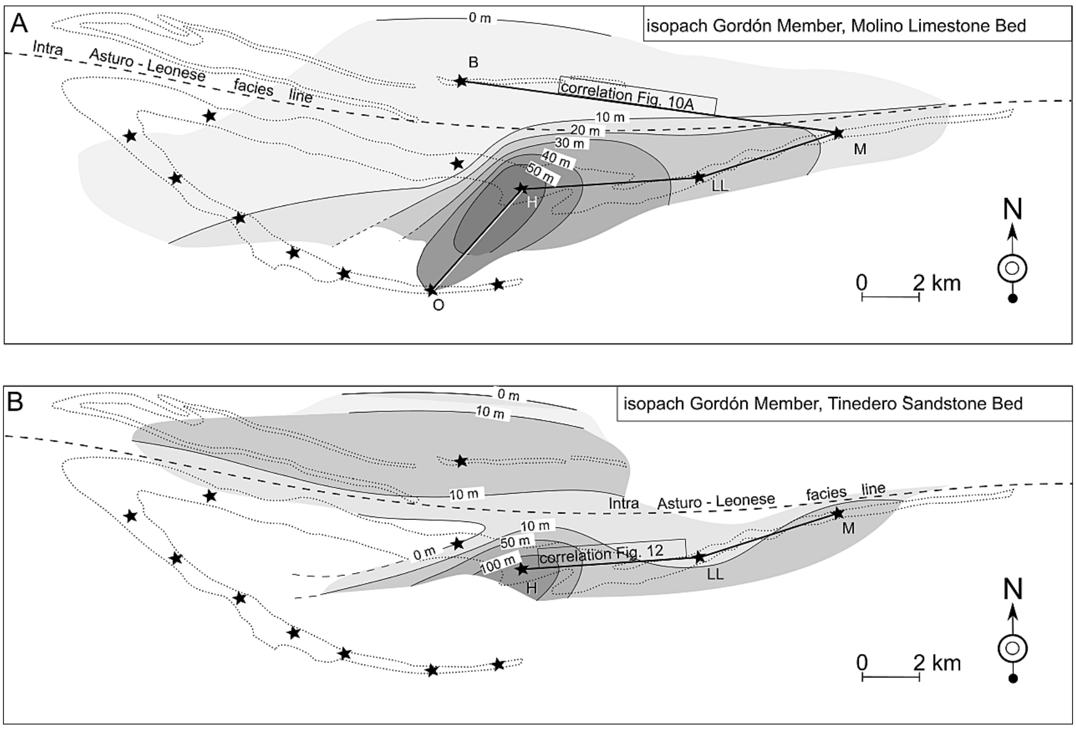

Fig. 9. Isopach patterns. **A** – Isopach pattern of the Molino Limestone Bed based on the thicknesses measured in the different sections. Backround map and section names as Fig. 1C. Stratigraphic correlation of Fig. 10A indicated by the connection line between the sections; **B** – Isopach pattern of Tiñedero Sandstone Bed based on the thicknesses measured in the different sections. Backround map and section names as Fig. 1C. Stratigraphic correlation of Fig. 12A indicated by the connection line between the sections

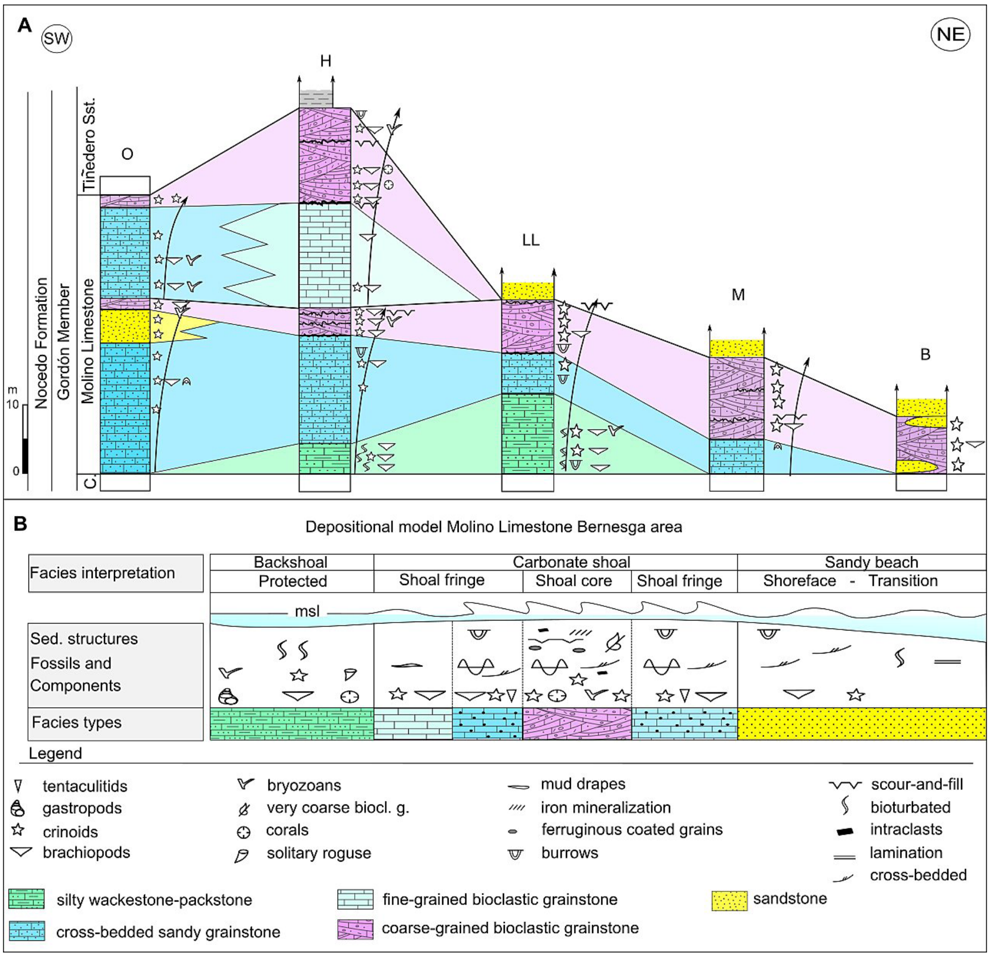

Fig. 10. Lithostratigraphic correlation and sedimentation model of the Molino Limestone. **A** – Correlation scheme of the Molino Limestone; **B** – Depositional model of the Molino Limestone (after Van Loevezijn & Raven 2017). For location of sections see Figure 1.

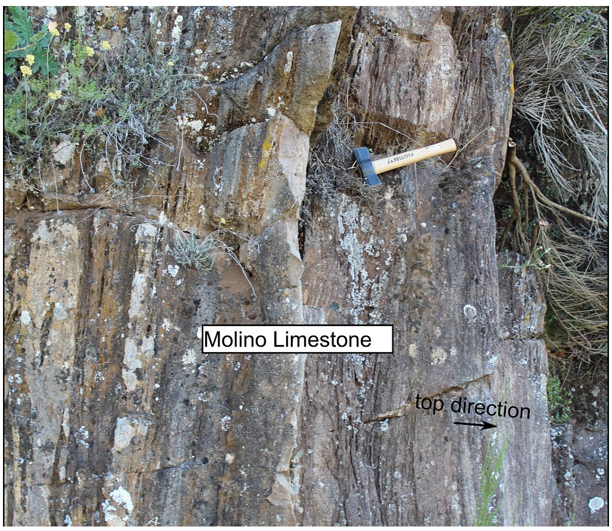

Fig. 11. Coarse-grained bioclastic grainstone facies of the Molino Limestone, with erosion surfaces, intraclasts and ferruginous mineralisation, section Matallana. For location of sections see Figure 1.

punctata Zone, and the Lower *Pa. hassi* Zone, early-middle Frasnian in age. In addition, the limestone is also rich in other fauna elements; sponges, corals, bryozoans, echinoderms, brachiopods, molluscs, tentaculites (see the list of Molino fossils in Van Loevezijn & Raven, 2017).

Interpretation: The Molino lithofacies types represent a backshoal environment (wackestones and packstones), a shoal fringe environment (sandy grainstones and fine-grained bioclastic grainstones), and the shallowest, high-energy environment, representing the shoal core (coarse -grained bioclastic grainstones). The facies types are arranged in two coarsening shallowing-upward cycles (Van Loevezijn & Raven, 2017). The distribution pattern of the Molino Limestone (Fig. 9A) shows, that sedimentation was connected to the transitional area between the Frasnian bathymetrical centre in the southwest, and the depositional highs of the Asturian Geanticline and the Pardomino High in the northeast; the limestone represents a skeletal carbonate shoal belt in a shallow marine, mixed siliciclastic-carbonate environment, between the north-eastern land area, and the deeper siliciclastic shelf in the southwest.

5.5. Gordón Member; Tiñedero Sandstone Bed

Name, type section and extension: The sandstone succession is named after the hill slope of the type locality in the section of Huergas de Gordón, 700 m south of the village, along the east side of N630 road to León (lat.: 42°50′15″ lon.: –5°39′19″). The succession occurs in the Intermediate and External zones of the Asturo-Leonese facies area, where it rests on the Molino Limestone. Therefore, the spatial distribution of the Tiñedero Sandstone is connected to the occurrences of the Molino Limestone (Figs 1, 9B). A thinly developed ferrugious, cross-bedded succession occurs in the eastern part of the Bernesga area near Matallana and Llombera (4–13 m). Towards the west near Huergas de Gordón, the thickness increases to more than 100 m, with limestone and siltstone intercalations. Further to the southwest, a thin sandstone succession rests probably on top of the Molino Limestone, but vegetation is abundant in this area between Sagüera and Olleros de Alba, resulting in poorly exposed sections. Thickness ranges between 0 and 108 m.

Boundaries: The Tiñedero Sandstone in the External Zone is always sandwiched between the underlying Molino Limestone, and the overlying succession of the Millar Member separated by sequence boundary 2. In the Intermediate zone sequence boundary 4 separates the unit from the overlying Llombera Beds.

Lithologic description: A wide variety of lithologies are intercalated in the sandy unit of the Tiñedero Sandstone; cross-bedded sandstones, bioturbated calcareous sandstones, calcareous siltstones, sandy, cross-bedded grainstones, and muddy wackestones (Fig. 12). Ferruginous crusts and iron mineralisation occur in the thin cross-bedded sandstone successions near Llombera and Matallana.

Biostratigraphy: García-Lopez & Sanz-Lopez (2002) correlated a conodont fauna from the wackestone intercalations in the Huergas de Gordón section, about 36 m above the base of the unit, with the Upper *Pa. hassi* Zone, middle Frasnian.

Interpretation: The poorly sorted, mud supported bioturbated siltstones, sandstones and muddy limestones represent low-energy quiet water condi-

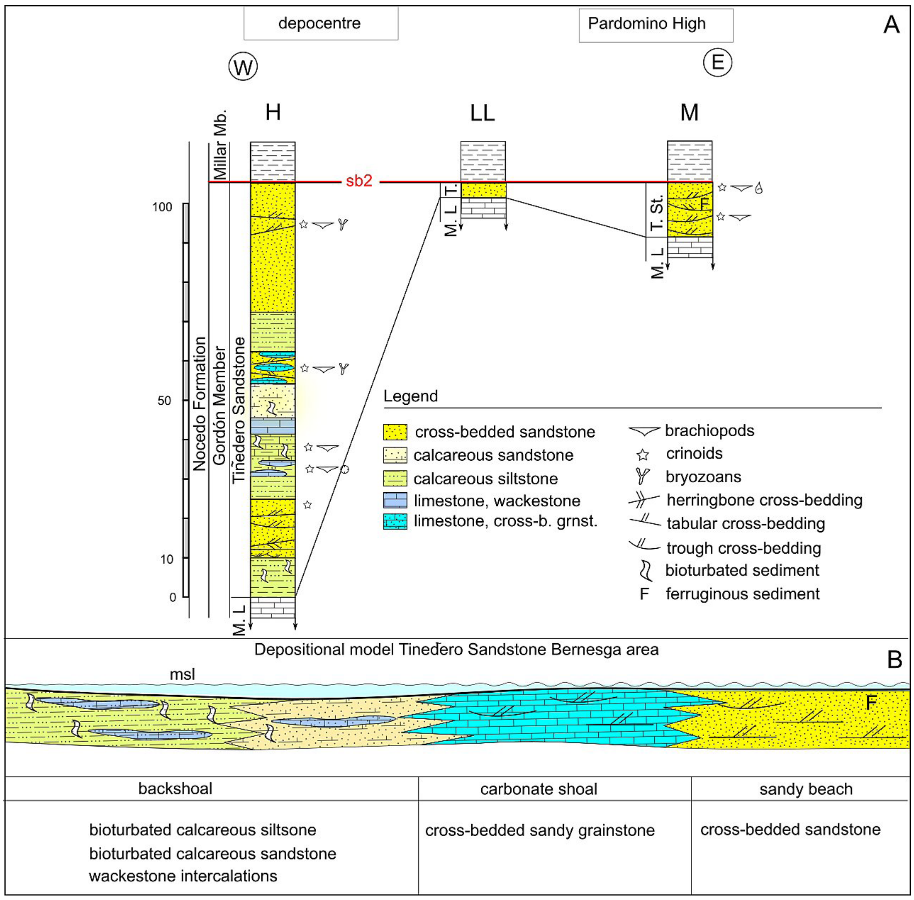

Fig. 12. Lithostratigraphic correlation and sedimentation model of the Tiñedero Sandstone. **A** – East-west correlation of the Tiñedero Sandstone; **B** – Depositional model of the Tiñedero Sandstone. L. – Molino Limestone, T – Tiñedero Sandstone. For location of sections see Figure 1.

tions, and can be correlated with the variably bedded mudstones, wackestones and packstones of the lagoonal facies belt of Bruchette & Wright (1992) and Schlager (2005). The cross-bedded sandstones and sandy limestones with their erosive bed contacts and channels, indicate shallow marine agitated water environment with shifting sediment load. These deposits belong to the shoal cross-laminated facies of Burchette & Wright (1992) and the grainstone facies belt of Schlager (2005). The gradual transitions between the muddy silty limestones and the cross-bedded sandstones and sandy limestones suggest a genetically relation.

6. Nocedo Formation; Millar Member

The max. 120 m thick Millar Member occurs in the outermost area of the Cantabrian Zone, the External Zone (Fig. 1), where it is sandwiched between the underlying Gordón Member of the Nocedo Formation, and the overlying Fueyo Formation, bounded by the surfaces sb2 and sb3. The member consists of three lithological units. For each unit a name is here introduced: from base to top the Villar Shale, the Pisones Shale, and the Regidero Sandstone (Fig. 2B). These units have gradual boundaries, are genetically related, and constitute a single sedimentological sequence. Their relations will be explained in their respective depositional models.

6.1. Millar Member; Villar Shale Bed

Name, type section and extension: The shale unit is named here Villar Shale, after a valley near the village Piedrasecha. The type section is located just south of the village, uphill on the east side (lat.: 42°49′22″ lon.: –5°46′43″). The unit occurs in the External Zone of the Asturo-Leonese facies area (Fig. 1), and ranges between 120–135 m in the southernmost locations, to thin, few meters thick, successions in the northeast and northwest (Fig. 13A). The eastern, thin, succession is exposed in the valleys of Llombera (17 m) and Matallana (5 m). In the southern sections the unit is well exposed in the section Sagüera, and the upper half of the unit can be seen in the section Portilla.

Boundaries: The Villar Shale is underlain by the sandstones of the Cantera Sandstone or Tiñedero Sandstone, separated by the sharp bounding surface of sequence boundary sb2. Sb2 is restricted to the External Zone, and is a flat, sharp bedding plane with no relief. The bounding surface represents a large contrast in facies, and marks a basinward facies jump from the sandy and calcareous shallow-marine shoreface sandstones of the Gordón Member to the distal offshore fines of the Millar Member. Updip, towards the inner part of the Asturo-Leonese Basin in the Intermediate and Internal Zones, the sb2 surface is eroded by sb4. The Villar Shale gradually merge upward into the sandy shales of the Pisones Shale (Fig. 14). In the southern part of the study area, where the unit is more than 100 m thick, the Pisones Shale, and overlying Regidero Sandstone are absent, and the Villar Shale constitutes the entire Millar Member, bounded by sequence boundaries sb2 and sb3.

Lithologic description: The Villar Shale consists of finely laminated, grey-brown shale, locally with intercalations of thin (1 to 3 mm thick) silt layers. This lithology show low degree of bioturbation and fossils are scarce; occasionally few thin-shelled brachiopods and crinoids occur.

Biostratigraphy: Little useful biostratigraphic information on the age of the Villar Shale is available; García-Lopez & Sanz-Lopez (2003) correlated a conodont fauna from underlying wackestone intercalations of the Tiñedero Sandstone, with the Upper *Pa. hassi* Zone, middle Frasnian in age. The fossiliferous biostromal limestone in the top of the Millar Member in the Esla area (the Crémenes Limestone of Rupke, 1965) corresponds probably with the Regidero Sandstone in the Bernesga area, and indicates probably the latest Frasnian (Van Loevezijn et al., 1986; García Alcalde, 2012). Therefore, the Villar Shale, and the overlying Pisones Shale and Regidero Sandstone of the Millar Member, are probably late Frasnian in age.

Interpretation: The laminated shales represent a low-energy, offshore environment, outside the coastal sandy zone, where thin silt intercalations represent suspension load from storm-generated flows transported far into the offshore area, where only the finest sediment settled down, and with a poor macrofauna (Reineck & Singh, 1975; Einsele, 2000). The sandy successions of the overlying sandy Pisones shales and Regidero sandstones constitute the near-coastal depositional areas of the same depositional sequence.

6.2. Millar Member; Pisones Shale Bed

Name, type section and extension: The sandy shale unit is named here Pisones Shale, after the hillslope west of Matallana the Torío. The selected type section is located in the riverbed of the Rio Torío, downstream of the water mill of Matallana, where exposure is excellent (lat.: 42°51′2″ lon.:

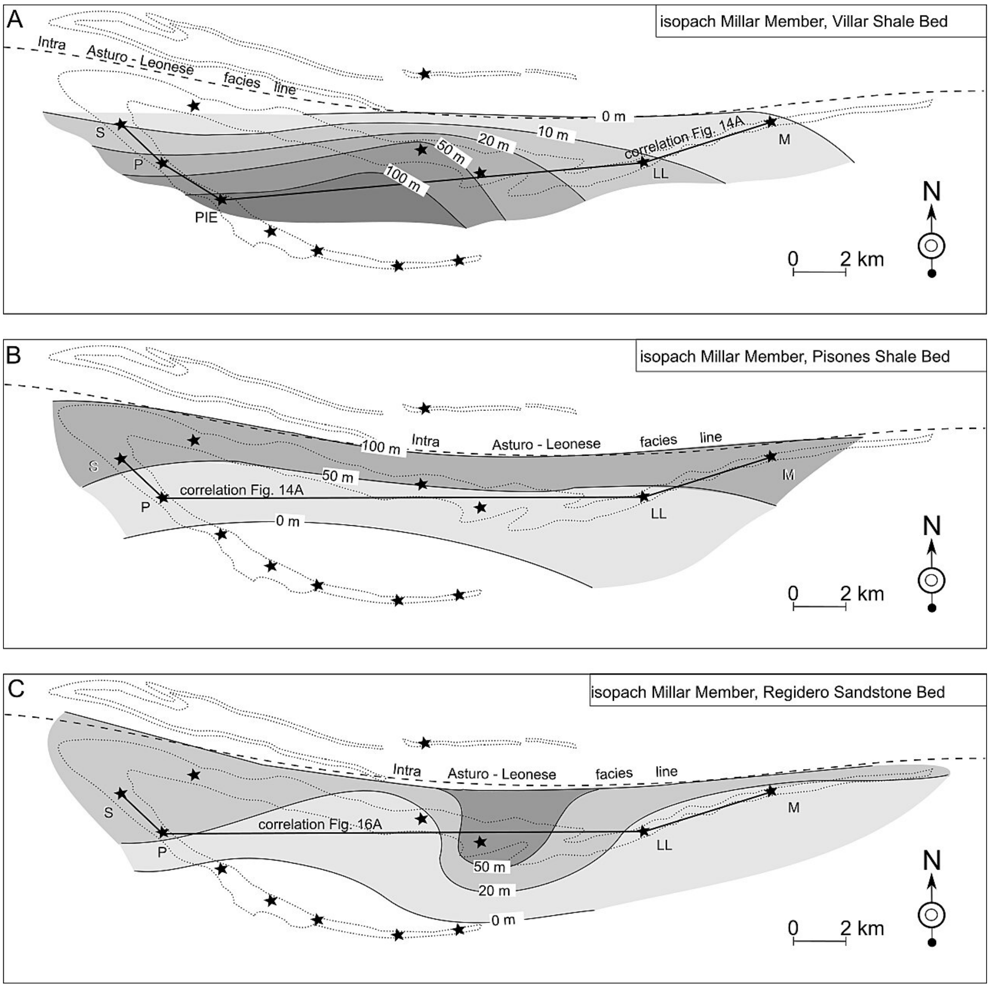

Fig. 13. Isopach patterns. **A –** Isopach pattern of the Villar Shale Bed based on the thicknesses measured in the different sections. Backround map and section names as Fig. 1C. Stratigraphic correlation of Fig. 14A indicated by the connection line between the sections; **B –** Isopach pallern of the Pisones Shale Bed based on the thicknesses measured in the different sections. Backround map and section names as Fig. 1C. Stratigraphic correlation of Fig. 14A indicated by connection line between sections; **C –** Isopach pattern of the Regidero Sandstone Bed based on the thicknesses measured in the different sections. Backround map and section names as Fig. 1C. Stratigraphic correlation of Fig. 16A indicated by the connection line between the sections.

–5°31′31″). However, one should exercise caution when entering the river; the Río Torio is a wild river and can only be accessed during the summer when water level is low. Another good exposure of the unit is situated at the east bank of the Arroyo de Llombera, a narrow valley, just southeast of the village Llombera (lat.: 42°50′8″ lon.: –5°34′49″). The Pisones Shale occurs in the External Zone of the Cantabrian Zone (Fig. 1), with a thickness between 50 and 100 m close to the Intra Asturo-Leonese facies line. Southward its thickness reduces fast, and in the southern most sections the unit is absent (Fig. 13B).

Boundaries: Near the transition between the Villar Shale and the overlying Pisones Shale, the number and thickness of sandstone intercalations gradually increase upward. Therefore, the boundary between the shales of the Villar Shale and the overlying sandy shales of the Pisones Shale is an arbitrary boundary. It is drawn above the lowermost sandstone bed with a thickness of at least 8 cm. It was considered to merge the Villar and Pisones Shale units into one shale unit. However, the lithological character of such a unit changes upward considerable from shales for the lower half to shaly sandstone for the upper half. The boundary between the Pisones Shale and the overlying Regidero Sandstone is always a gradual transition from sandy shale to sandstone (Fig. 15).

Lithologic description: The Pisones Shale is a heterolithic succession of bioturbated silty shales with rhythmic intercalations of grey-brown, graded

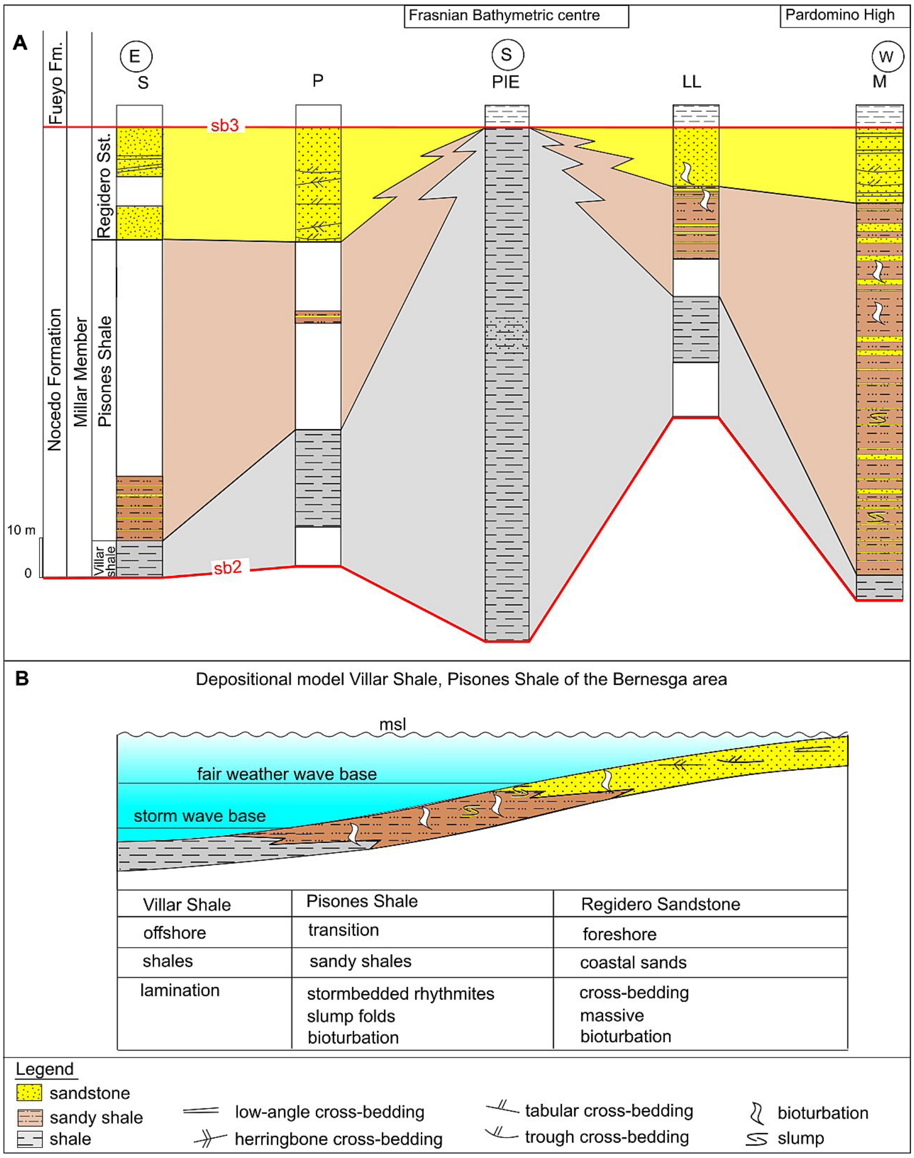

Fig. 14. Lithostratigraphic correlation and depositional model of the Villar Shale, the Pisones Shale and Regidero Sandstone. **A** – East-west correlation of the lithological units of the Millar Member; **B** – Depositional model of the Millar Member with the Villar Shale, the Pisones Shale and the Regidero Sandstone. For location of sections see Figure 1.

very-fine grained sandstone beds, 8–10 cm thick, locally up to 30 cm thick, with erosional sharp bases and sharp tops. The succession contains an upward increase of sandstone bed intercalations with many slump and load structures. Internally the sandstone beds contain a structureless or parallel to subparallel laminated lower part, overlain by a swaly-laminated wave-ripple succession (Van Loevezijn, 2022).

Biostratigraphy: Like the underlying Villar Shale, few useful biostratigraphic information on the age is available for the Pisones Shale. Based on the underlying Molino Limestone fauna and from data of the Crémenes Limestone east of the Bernesga area in the Esla area, (García-Lopez & Sanz-Lopez, 2003; Van Loevezijn et al., 1986), the Pisones Shale probably represent the upper Frasnian.

Interpretation: The internal structures of the sandstone beds resemble the sedimentary structures and facies types associated with hummocky cross stratification generated by storm waves of Einsele (2000), Jelby et al. (2020) and others. Storm deposits or tempestites formed in the transition depositional zone between shoreface and offshore (Reineck & Singh 1975; Einsele 2000). The thickest storm bedded successions occur close to the northern edge of the External Zone. To the south thickness and sand percentage decrease; there, the sandy shales of the Pisones Shale Bed are gradually replaced by the shales of the Villar Shale Bed.

6.3. Millar Member; Regidero Sandstone Bed

Name, type section and extension: The unit is named here Regidero Sandstone, after 'El Fuente de Regidero' a water well in the type section, located at

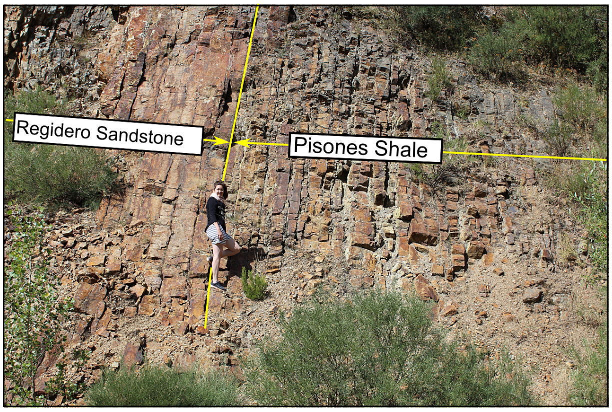

Fig. 15. Gradual transition from the Pisones Shale to the Regidero Sandstone, Arroyo de Llombera, type locality of the Regidero Sandstone. For location of section LL see Figure 1.

the Arroyo de Llombera, a small valley southeast of the village Llombera (lat.: 42°50′7″ lon.: –5°34′53″). The Regidero Sandstone occurs in the External Zone of the Cantabrian Zone (Fig. 1), and has a general thickness between 20 and 50 m close to the Intra Asturo-Leonese facies line, with an exceptional thick succession of 75 m near Huergas de Gordón. Southward its thickness reduces fast, and in the southernmost sections the unit is absent (Fig. 13C).

Boundaries: The contact between the underlying Pisones Shale and the Regidero Sandstone is a gradual transition from sandy shale to sandstone (Fig. 16). The sharp erosive bounding surface of sequence boundary sb3 separates the Regidero Sandstone from the dark-grey shales of the overlying Fueyo Formation (Fig. 14). The sb3 bounding surface separates the Nocedo Formation, Frasnian in age, from the overlying Fueyo Formation, Famennian in age. The surface is limited to the External Zone. Towards the inner part of the Asturo-Leonese Basin, in the Intermediate and Internal Zones, the surface is eroded by sb4. Sb3 is an erosional surface with a remarkable relief, and marked by an abrupt basinward shift in facies: it cuts down up to 8 m into the coastal sandstones of the Regidero Sandstone Bed (Matallana section), and is overlain by the offshore shales of the Fueyo Formation. In the southernmost sections of the External Zone the sb3 surface changes to a correlative conformity with no obvious erosional relief.

Lithologic description: A complete developed sandstone succession consists from bottom to top of grey-brown mottled, very bioturbated, silty, very-fine grained quartz sandstone, grey-brown, massive, bioturbated very-fine grained quartz sandstone, and light-yellow cross-bedded very-fine to fine grained quartz sandstone (Fig. 16).

Biostratigraphy: East of the Bernesga area, in the Esla area, at a proximally the same stratigraphic level as the Regidero Sandstone, in the top of the

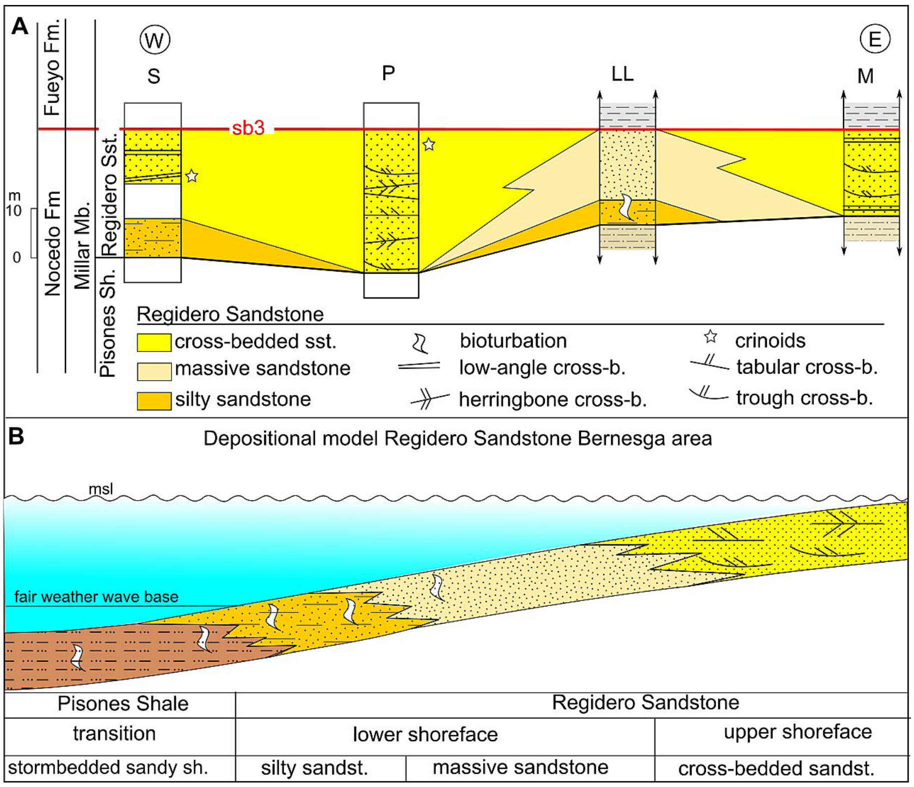

Fig. 16. Lithostratigraphic correlation and depositional model of the Regidero Sandstone. **A** – East west correlation of the Regidero Sandstone; **B** – Depositional model of the Regidero Sandstone. For location of sections see Figure 1

Millar Member, the Crémenes Limestone occurs. The rich CR3 fauna in the Crémenes 3 unit of the Aguasalio type section and adjacent sections indicates probably a latest Frasnian (Van Loevezijn et al., 1986; García Alcalde, 2012). A conodont fauna in the calcareous basal shales of the overlying Fueyo Formation at Piedrasecha represents the *Pa. triangularis* Zone, of lower Famennian age (Van Loevezijn, 1988). Therefore, the Regidero Sandstone represents probably the upper Frasnian.

Interpretation: The distribution pattern of the Regidero Sandstone is very similar to that of the underlying Pisones Shale, with a thick development in the northern areas of the External zone, and a thinning towards the south. The Villar Shale shows the opposite, with the thickest succession in the south. All three units are part of the same sequence, and thus part of the same depositional system; they are complementary, and together, they demonstrate a southward fining from sandy deposits in the north to shales in the south; the Regidero Sandstone represents the sandy coastal area of the system.

7. Sedimentation models and basin evolution

The subdivision of the two members of the Nocedo Formation results in a complex jigsaw of lithologies, summarised in Fig. 17: a total of eight units are distinguished. Their lateral distributions and their depositional environments are linked to the sedimentation model of the sequence they are part of.

The depositional area of the Gordón Member extended outside the External Zone to the north, where the thin Gordón succession (67–77 m) consists of calcareous bioturbated very fine-grained sediment of the Cantera Sandstone, overlain by a few meters of sandy limestones of the Molino Limestone, and capped by a thin ferruginous sandstone succession of the Tiñedero Sandstone. In the External Zone sediments were laid down on a gradual shallowing upward depositional profile resulting in extensive lithosomes with gradational boundaries between the lithologies. The depositional centre was located in the central part of the Bernesga area where the fines of the Saloja Siltstone are overlain by the shoreface sandstones of the Cantera Sandstone. The bathymetrical centre of the basin was located in the southwest, where the thickest Rebolleras Shale succession was deposited. The southwestern, basinward, progradation of the shallow-marine coastal area, resulted in a seaward shift and the formation of the coarsening-upward facies stack. The Cantera Sandstone is capped by the sandy, coarse-grained limestones of the Molino Limestone. They represent a condensed limestone succession of a shallow, high-energy environment, with channels, erosion surfaces, coarse bioclastic lags, reworked intraclasts, and mineralisation surfaces. This carbonate deposition in the upper part of the Gordón Member, breaks the cycle of siliciclastic deposition of the Nocedo Formation, that is later resumed again in the Millar Member. The siliciclastic succession of the Gordón Member represents a shallowing upward wedge in the distal parts of the Asturo-Leonese shelf (van Loevezijn & Raven, 2020). The strength of the currents plays an important role in the siliciclastic distribution and is related to sea level (Zeller et al., 2015). Effective lateral transport of clastics on the shelf is only possible when the water depth is enough for a current system to exist. As the water depth decreases the input of siliciclastics will therefore decrease, and carbonate sedimentation will take over. Carbonate production will cause a further reduction of the accommodation space which leads to carbonate dominance in the upper part of the shallowing upward cycle of the mixed siliciclastic carbonate environment of the Gordón Member (van Loevezijn & Raven, 2017). On top of these limestones the Tiñedero Sandstone was deposited; a mix of sandy limestone and cross-bedded sandstone of a (carbonate) shoal environment, with intercalations of muddy limestone beds, and sandy siltstones, representing a low-energy backshore environment.

The Millar Member occurs in the External Zone of the Asturo-Leonese facies area and is bounded in the north by the Intra Asturo-Leonese facies line. Close to the facies line in the north and northwest, the 100 m thick tempestite succession of sheet-like sand and shale beds of the Pisones Shale is overlain by the coastal sands of the Regidero Sandstone. These shallow-marine sandy deposits pinch out to the south where the bathymetric centre of the basin was located, and are replaced by the offshore fines of the Villar Shale.

8. Conclusions

The Nocedo Formation has been subdivided into a lower Gordón Member and an upper Millar Member, based on a sequence stratigraphic approach, and therefore do not have a uniform lithological character. In this study these members are subdivided into different lithological beds. A total of eight are recognised; five Gordón beds and

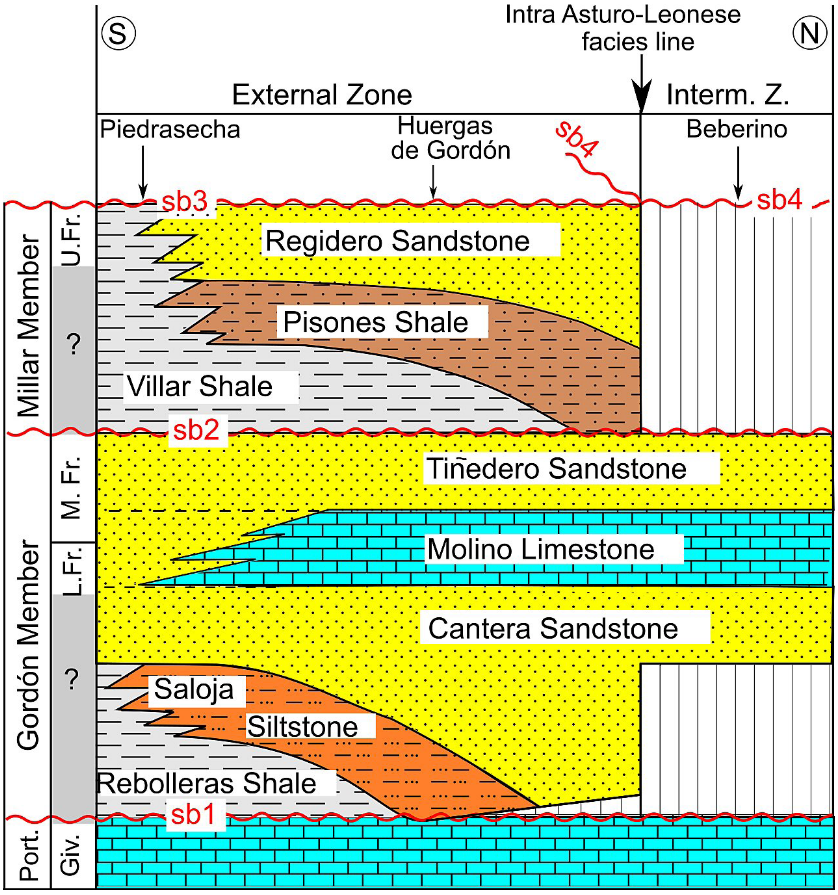

Fig. 17. Lithostratigraphic correlation panel of the Bernesga area, Cantabrian Zone, Spain. L.F. – Lower Frasnian, M.Fr. – Middle Frasnian, U.Fr. – Upper Frasnian.

three Millar beds. Each bed represents a part of the depositional model of the corresponding member. Within each sequence they have gradational contacts, and their lateral distribution is consistent and complementary. Together they show the paleogeographic scheme of the depositional sequence they belong to.

The beds of the Gordón Member were deposited on a gradual depositional profile, and can be divided into three depositional areas. In the northeastern part of the basin a thin fine-grained succession was deposited in sheltered areas with intercalations of high-energy deposits, including carbonate shoals, with erosional surfaces and hardgrounds (Cantera Sandstone Bed, Molino Limestone Bed, Tiñedero Sandstone Bed). The successions in the central part of the basin consist of thick well-developed, prolonged, coarsening-upward successions from the Rebolleras Shale Bed, grading upward to the Saloja Siltstone Bed capped by a thick sandstone package of the Cantera Sandstone Bed, overlain by the Molino Limestone Bed and the Tiñedero Sandstone Bed, indicating a shallowing upward from offshore–transition to foreshore environments with sheltered depositional areas. Finally, the southernmost sections of the outer part of the basin, are characterized by a well-developed succession of the Rebolleros Shale Bed, a thin Saloja Siltstone Bed, overlain by the Cantera Sandstone Bed with discontinuous limestone lenses of the Molino Limestone Bed, and capped by a thin Tiñedero Sandstone Bed.

The Millar Member occurs in the External Zone south of the Asturo-Leonese facies area. The laminated shale succession of the Villar Shale Bed is well developed in the southwestern most area, and represents a low-energy, offshore environment. Towards the north the bed is thinning and (partly) replaced by the sandy deposits of the Pisones and Regidero Beds, which are thick developed close to the facies line in the north, and thin towards the south. The Pisones Shale Bed and the Regidero Sandstone Bed are the lateral equivalent of the upper part of the Villar shale Bed.

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