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RESEARCH ARTICLE

Stratigraphic architecture of the Gordón Member, and its paleogeographic implications (Frasnian, Cantabrian Mountains, Spain)

Arquitectura estratigráfica del Miembro Gordón y sus implicaciones paleogeográficas (Frasniense, Cordillera Cantábrica, España)

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Keypoints:

Description of the stratigraphic architecture of the Frasnian clastic wedge of the Gordón Member, Cantabrian Zone.

Establishment of stratigraphic relations of the Gordón Member between the Sil area and the Bernesga area.

Frasnian-Famennian uplift of the core area of the Cantabrian Zone is documented in the depositional shift of the Upper Devonian clastic wedges.

ABSTRACT

The Gordón Member (lower-middle Frasnian, sequence A) of the Cantabrian Zone forms an asymmetric depositional cycle, characterized by a basal thin, transgressive fining-upward part, indicating the early Frasnian transgression against the Cantabrian Massif towards the north, and a distinct overlying coarsening- and shallowing-upward package, when the available accommodation space was filled. A tectonic shortening by thrusts and folds in the southern part of the Somiedo–Correcilla Unit of 41% is estimated. From the restored original extent, the Gordón depositional environment is re-interpreted as a southward sloping, mixed siliciclastic-carbonate shelf. There is a change in basin configuration from an extensive gentle dipping profile (sequence A), to a narrow steeper profile with an increase in the depositional dip (sequences B, C), caused by uplift and enlargement of the core area of the Cantabrian Zone, and subsidence of the External Zone.

Keywords: Frasnian; Peripheral bulge; Clastic wedge; Cantabrian Zone

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Puntos clave:

Descripción de la arquitectura estratigráfica de la cuña clástica frasniense del Miembro Gordón, Zona Cantábrica.

Caracterización de las relaciones estratigráficas del Miembro Gordón entre las áreas del Sil y Bernesga.

Se documenta el levantamiento del núcleo de la Zona Cantábrica durante el Frasniense-Fameniense y la migración deposicional de las cuñas clásticas del Devónico Superior.

RESUMEN

En la Zona Cantábrica, el Miembro Gordón (secuencia A del Frasniense inferior-medio) presenta un ciclo deposicional asimétrico caracterizado por una delgada secuencia basal granodecreciente indicando la transgresión hacia el Norte del Frasniense inferior sobre el Macizo Cantábrico, a la que se superpone una secuencia somerizante granocreciente, indicando la progresiva colmatación del espacio de acomodación existente. Una estimación del acortamiento tectónico del 41% es asumida para la parte meridional de la Unidad de Somiedo–Correcilla. Restaurado hasta la extensión inicial, el ambiente deposicional para el Miembro Gordón se reinterpreta como una plataforma mixta, siliciclásticos y carbonatos, con una morfología suave con pendiente hacia el sur. El levantamiento y crecimiento del área central de la Zona Cantábrica junto a la subsidencia de la Zona Externa próxima durante el Frasniense superior Fameniense, fue responsable del desplazamiento del área de sedimentación desde un área de plataforma amplia (Secuencia A; zonas intermedia y externa) hacia un área reducida en la parte más externa del borde de la Zona Cantábrica (Secuencias C y B; zona externa).

Palabras clave: Frasniense; Bulto periférico; Cuña clástica; Zona Cantábrica

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1. Introduction

The onset of the Upper Devonian terrigenous (sandy) sedimentation indicates the end of the extensive Lower and Middle Devonian carbonate platforms of the Cantabrian Zone, and a Late Devonian shift to mainly siliciclastic sedimentation. The turnover from the Middle Devonian carbonates of the Portilla Formation to the Upper Devonian sandstones of the Nocedo Formation is one of the major Devonian transitions with a regional correlation. The Frasnian Nocedo Formation (Comte, 1959) consists of two clastic wedges, deposited on the outer rim of the Cantabrian Zone. The present study focuses on the Gordón Member (Van Loevezijn, 1983), the lower unit of the Nocedo Formation. The member records the gradual transformation to Variscan tectonic settings, when a foreland bulge developed in the core area of the Cantabrian Zone (Keller *et al.*, 2008; Van Loevezijn, 2020).

The Upper Devonian succession shows marked changes in facies and thickness over short distances (Sánchez de la Torre, 1977; Sanchez de la Torre *et al*., 1983; Van Loevezijn, 1986). This poses us with a problem; the interpreted stratigraphic north–south profile of the southern Cantabrian Mountains displays an unrealistic steep stratigraphic prism, with thin, coarse-grained northern successions (Pedroso syncline) and adjacent, thick, fine-grained southern successions (Alba syncline), with the Sabero-Gordón fault zone in between. In this study an attempt is made to restore the original width of the area by palinspastic restoration accounting for folding and thrust displacement, to interpret the architecture of the Upper Devonian sequence studied (Gordón Member of the Nocedo Formation), and to present a more realistic, dip wise stratigraphic profile. Finally, the vertical facies patterns and the lateral continuity of the Gordón Member is compared with the overlying Upper Devonian clastic wedges to document the evolution of the Upper Devonian Cantabrian Basin.

2. Geological setting

The Palaeozoic rocks of the Cantabrian Mountains of northern Spain belong to the Cantabrian Zone, a part of the Palaeozoic Iberian Massif (Fig. 1A) (Lotze, 1945). They represent the external thrust and fold belt of the Iberian Variscan orogen in northwestern Spain (Alonso *et al*., 2009). The Palaeozoic succession includes a pre-orogenic pre-Carboniferous succession, and an Uppermost Devonian–Mississippian to Westphalian syn-orogenic succession. (Marcos & Pulgar, 1982; Alonso *et al*., 2015). Later, Van Loevezijn (2023) interpreted the Upper Devonian succession as a transitional phase between pre-orogenic and syn-orogenic stages. According to the interpretations of Keller et al. (2008) and Van Loevezijn (2020) the initiation of the Variscan foreland basin system is demonstrated by the Late Devonian development of a hinge line that separated a peripheral bulge area in the core of the Cantabrian Zone from the adjacent depositional area of a foredeep (Fig. 1B).

During the Silurian and most of the Devonian a pre-orogenic shallow-marine succession was deposited across extensive stable shelf areas: the Asturo–Leonese facies of Brouwer (1964), located in a strip around the core of the Cantabrian Zone, the positive area of the Asturian Geanticline or Cantabrian Massif (Van Adrichem Boogaert, 1967; Raven, 1983; Aramburu *et al*., 2004). The Intra Asturo–Leonese facies line separates the outermost depositional area, with a thick Upper Devonian succession, from the inner part of the Asturo-Leonese facies area, with a thin truncated Upper Devonian succession (Raven, 1983; Van Loevezijn, 1986). In this study we investigate how this element fits our new interpretation of the basin profile, which takes into account the Variscan shortening. The Palencian facies area in the east (Brouwer, 1964) is the pelagic equivalent of the shelf facies. It is allochthonous and represents the deeper south (western) continuation of the Asturo–Leonese facies (Frankenfeld, 1984; Keller *et al*., 2007; Weil *et al.,* 2013).

The first record of instability in the passive margin settings is interpreted to have occurred in Late Devonian times, indicating the onset of the Variscan orogeny, as the subduction turned from oceanic to continental, and consequently the margin shifted from passive to active (Keller *et al*., 2008; Díez Fernández *et al*., 2016). According to this, the older sedimentary succession in the core area of the Cantabrian Zone would have emerged, and their erosion products would have been deposited as Upper Devonian prograding clastic wedges in the outermost part of the zone (Van Loevezijn, 2020). The repeated uplifts would be

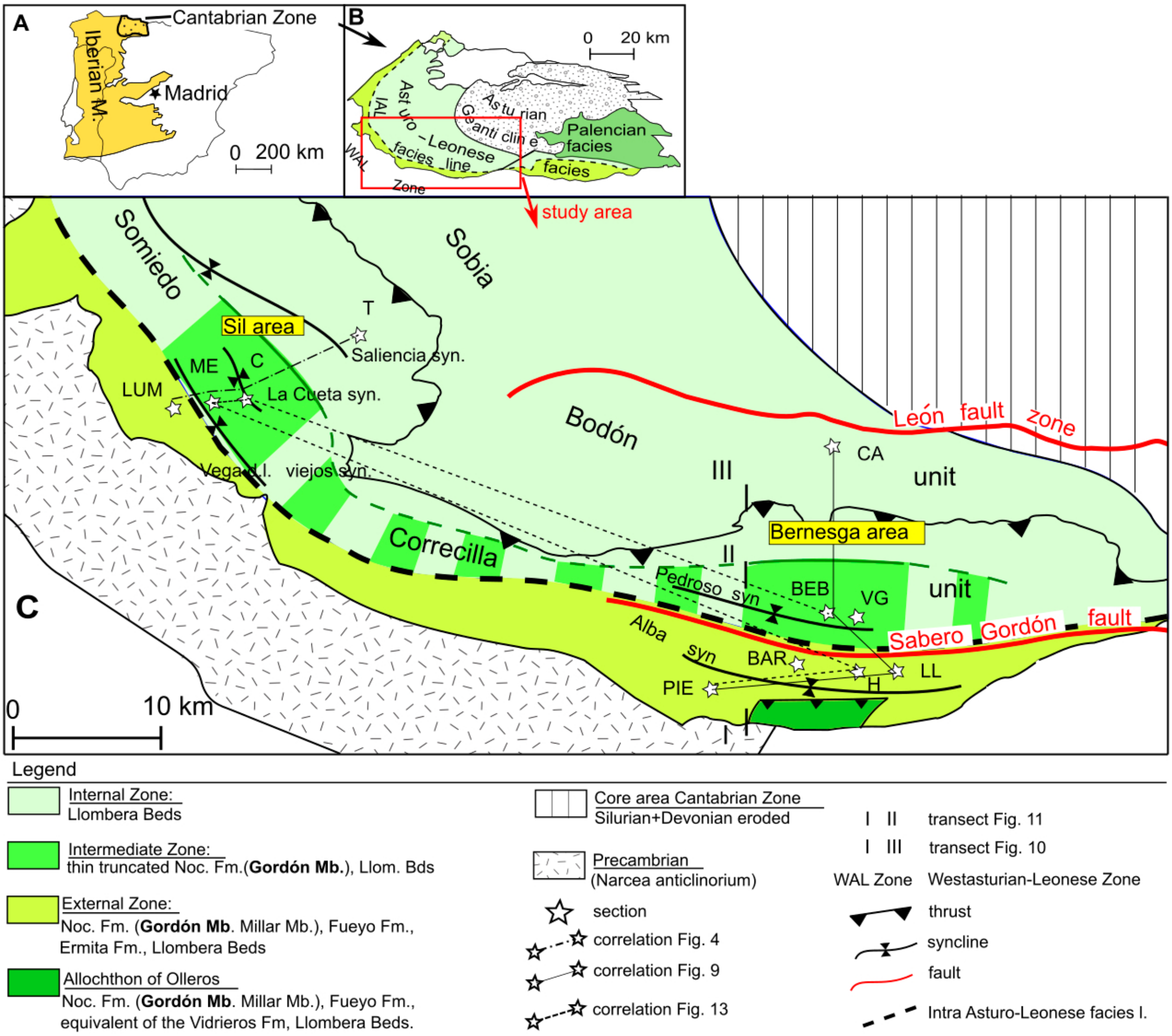

Figure 1. A) Situation map with the location of the Cantabrian Zone. B) Map of the Cantabrian Zone with the major Devonian palaeogeographic units and the outline of the study area. C) Highly simplified map of the study area with the Devonian palaeogeographic units, and the locations of sections; Lum=Lumajo, ME=Meroy, C=La Cueta, PIE=Piedrasecha, BAR=Barrios, H=Huergas, LL=Llombera, BEB=Beberino, VG=Vega de Gordón, CA=Camplongo.

Figura 1. A) Mapa de situación con la localización de la Zona Cantábrica. B) Mapa de la Zona Cantábrica con las principales unidades paleogeográficas del Devónico y el contorno de la zona de estudio. C) Mapa muy simplificado del área de estudio con las unidades paleogeográficas del Devónico y la ubicación de las secciones; Lum=Lumajo, ME=Meroy, C=La Cueta, PIE=Piedrasecha, BAR=Barrios, H=Huergas, LL=Llombera, BEB=Beberino, VG=Vega de Gordón, CA=Camplongo.

recorded in the shallow-marine strip of the Asturo-Leonese facies area as sequence boundaries in the Upper Devonian succession (sequence boundaries 1 to 4) (Fig. 2), with tilting and erosion before the latest Late Devonian, resulting in the successive cut-out of strata towards the core of the Cantabrian Zone (sequence boundary 4, or Upper Devonian Unconformity). The overlying uppermost Famennian rocks rest on Devonian, Silurian, Ordovician, and Cambrian strata (Raven, 1983; Van Loevezijn, 2020).

2.1. Upper Devonian succession

The Upper Devonian deposits of the southern Cantabrian Zone are subdivided into three formations (Fig. 2): the Frasnian Nocedo Formation consisting of calcareous sandstones,

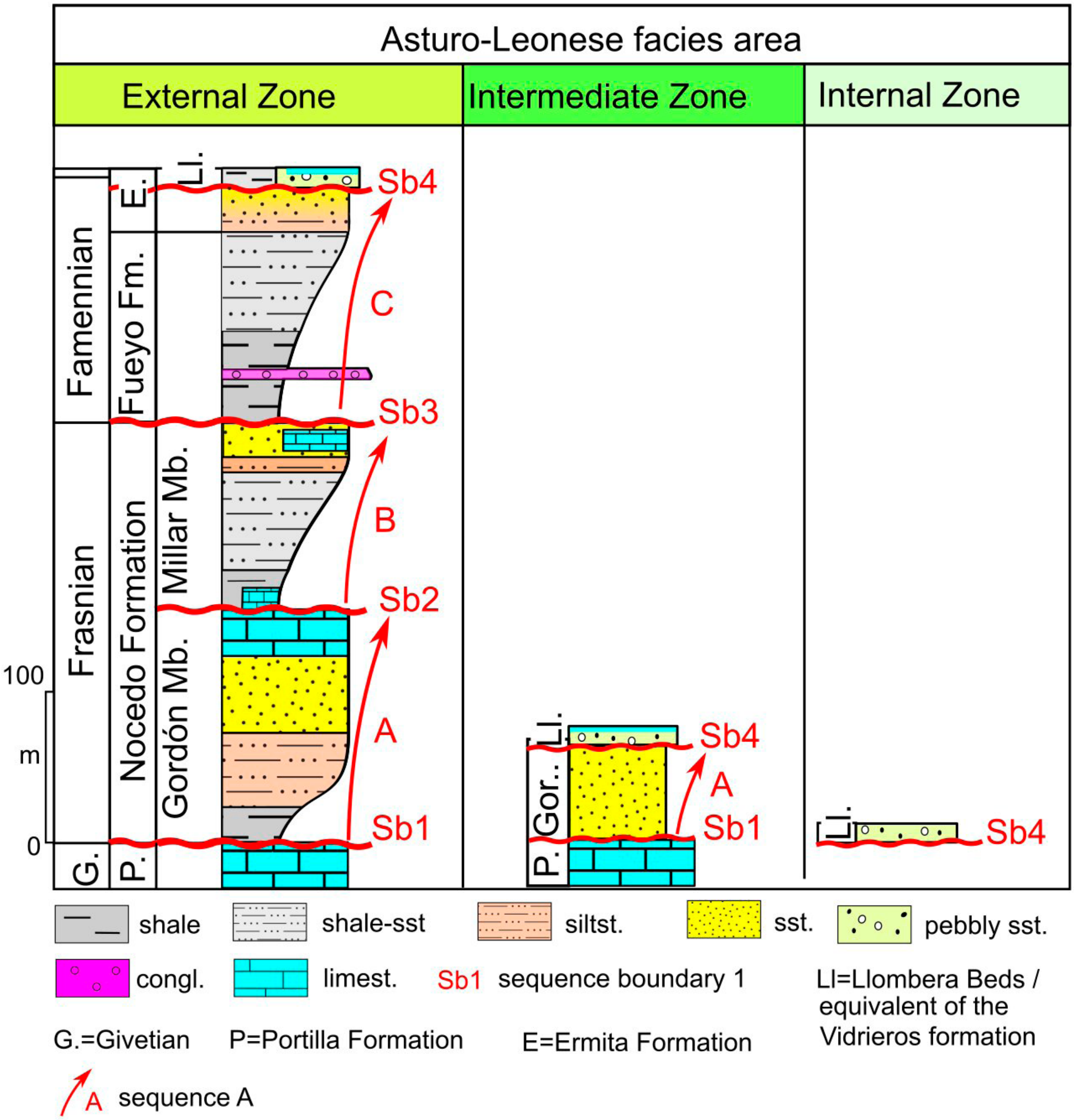

Figure 2. Upper Devonian stratigraphic subdivision of the southern Cantabrian Zone with the location of the sequence stratigraphic boundaries after Van Loevezijn & Van Loevezijn Peña (2017).

Figura 2. Subdivisión estratigráfica del Devónico superior de la Zona Cantábrica Sur con la ubicación de los límites estratigráficos de la secuencia según Van Loevezijn & Van Loevezijn Peña (2017).

the early Famennian Fueyo Formation consisting of shales and sandy shales with a conglomerate in the basal part, and the Famennian–early Tournaisian Ermita Formation mainly consisting of sandstones (Comte, 1959). Limestone intercalations occur at several stratigraphic levels (Van Loevezijn & Raven, 2017). These three units have been grouped by Van Loevezijn & Van Loevezijn Peña (2017) into three coarsening upward clastic wedges and an overlying thin transgressive unit, bounded by sequence boundaries sb1 to sb4. Each of these bounding surfaces represents an abrupt shift to deeper facies, and/or a regional erosional event (Van Loevezijn, 2020). The two Frasnian sequences correspond to the Gordón and Millar members, respectively, of the up to 425 m-thick Nocedo Formation. The third coarsening-upward wedge, Early Famennian in age, comprises the shales and sandy shales of the Fueyo Formation, up to 300 m thick, and the overlying sandstones of the Ermita Formation, up to 96 m thick (Van Loevezijn & Van Loevezijn Peña, 2017). Sequence boundary 4, the Upper Devonian Unconformity, separates the underlying clastic wedges from a thin, transgressive succession of sandy conglomerates, sandstones and coarse bioclastic limestones of variable thickness, forming the upper part of the Ermita Formation, and named as Llombera beds by Keller *et al*. (2008) and Van Loevezijn & Van Loevezijn Peña (2017). A thrust unit in the southern limb of the Alba syncline, the Allochthon of Olleros (Van Loevezijn, 2022b), contains a unique fine-grained Famennian succession (equivalent of the Vidrieros Formation), consisting of dark-grey shales with muddy limestone intercalations, and can be correlated with the coarse-grained Llombera beds (Van Loevezijn & Van Loevezijn Peña, 2017; Van Loevezijn, 2022b; Sanz-López & Blanco-Ferrera, 2023).

Based on the distribution of the Upper Devonian units, the Asturo–Leonese facies area can be subdivided into three facies zones (Fig. 1C): the External Zone including the four sequences described above, the Intermediate Zone with a truncated thin Gordón Member and the overlying Llombera beds, and the Internal Zone where the Upper Devonian clastic wedges are absent and the Llombera beds cut down into Givetian and older strata (Van Loevezijn, 1983, 1986).

2.2. Upper Devonian biostratigraphy

The Nocedo Formation is roughly dated by conodonts and other faunas (Van Loevezijn, 1986; García López & Sanz López, 2002; García Alcalde, 2012). The uppermost limestones of the Portilla Formation underlying the Nocedo Formation contain conodonts of the Givetian *hermanni-cristatus* Zone (García López & Sanz-López, 2002). Fossils in the basal part of the Gordón Member indicate a probable Frasnian age (Van Loevezijn, 2020). This places the base of the Gordón Member close to the Givatian–Frasnian boundary. However, the bounding surface between these formations is a sequence boundary (sb1), which is an unconformity updip with subaerial exposure and erosion, and a correlative conformity downdip (Van Loevezijn, 2020), and therefore, the upper part of the Portilla Formation is locally missing, as was demonstrated by Reijers (1972), Van Staalduinen (1973) and Raven (1983). A limestone intercalation in the upper part of the Gordón Member (Molino Limestone) was deposited from the Upper *falsiovalis* through the Lower *hassi* zones and the thin overlying limestone units contain conodonts of the Upper *hassi* Zone (García López & Sanz-López (2002). These data suggest that the Gordón Member can be correlated with the Lower–Middle Frasnian. The brachiopod fauna of the limestone intercalation at the top of the overlying Millar Member (CR3 fauna of the Crémenes Limestone; Westbroek, 1964; Van Loevezijn *et al*., 1986; García Alcalde, 2012) probably indicates a late Frasnian age, but some Famennian forms are also present, and the top of the Nocedo Formation is close to the Frasnian–Famennian boundary. The Fueyo Formation contains early Famennian conodont faunas (Van Loevezijn, 2022b), and the overlying transgressive Llombera beds and the equivalent of the Vidrieros Formation were deposited from the middle to upper *expansa* through *sulcate* zones (García López & Sanz-López, 2002; Van Loevezijn, 2022b). The Devonian–Carboniferous boundary is located within these beds, or in the overlying limestones of the Baleas Formation.

3. Stratigraphy and facies of the Gordón Member

From the Upper Devonian lithofacies types described by Van Loevezijn & Van Loevezijn Peña (2017), Van Loevezijn & Raven (2020), Van Loevezijn & Raven (2021) and Van Loevezijn (2022a), a total of ten facies types occur in the Gordón Member, grouped into seven facies associations, ranging from offshore to coastal environments. The descriptions and interpretations of these facies are summarized in Figure 3 and they will be briefly referred to in the description of the sections below. For a more detailed sedimentological description, the reader is referred to the above cited publications.

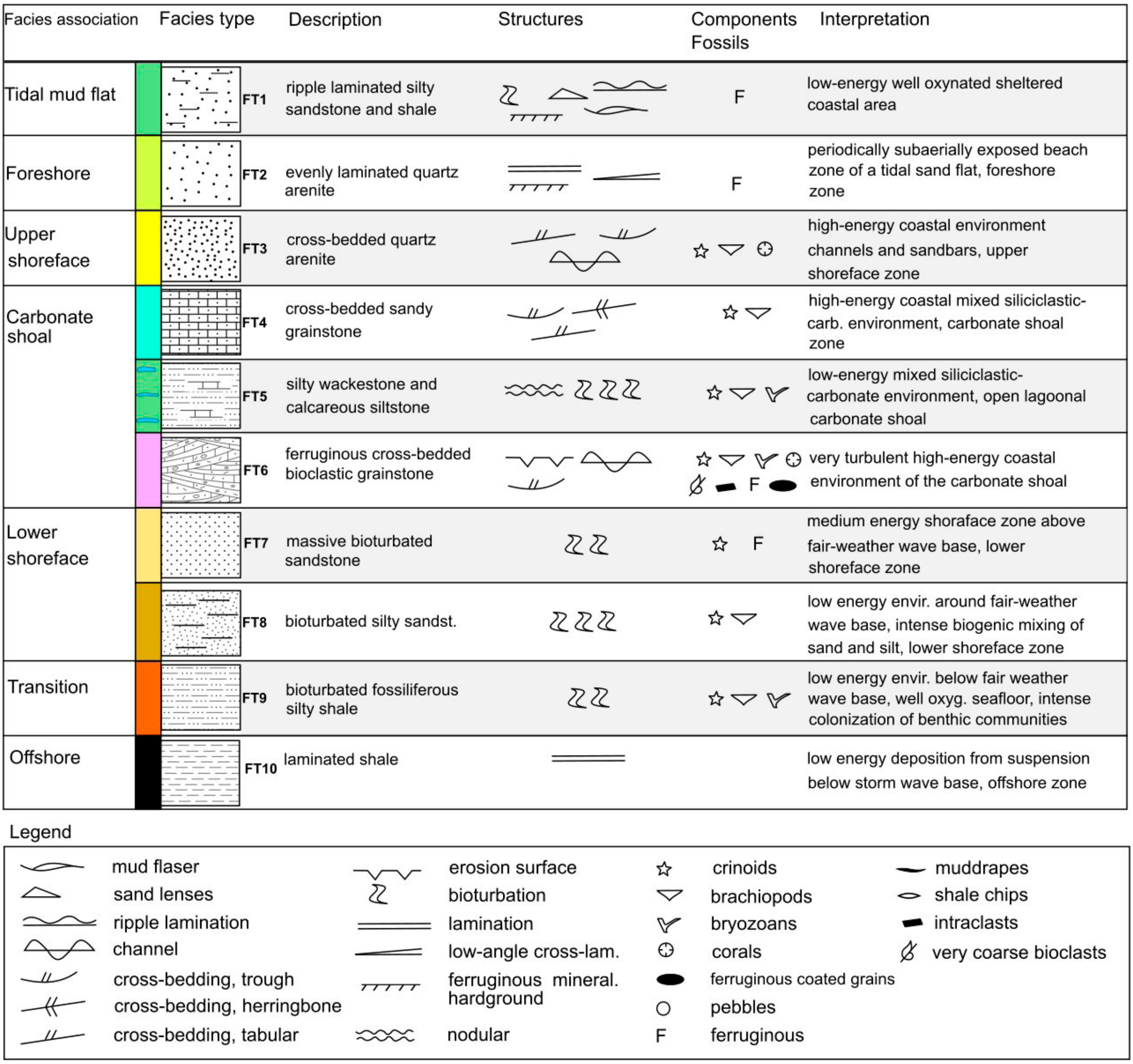

Figure 3. Facies types of the Gordón Member.

Figura 3. Tipos de facies del Miembro Gordón.

3.1. Sections Sil area

Description: The Gordón Member is 169–267 m and crops out in the Vega de los Viejos and La Cueta synclines, having been studied in the Lumajo, Meroy and La Cueta sections (Fig. 4). It sharply overlies the Portilla Formation by means of sb1, which at La Cueta and Lumajo sections consists of a flat surface bounding the light grey bioclastic Portilla limestones and the basal Gordón calcareous siltstones or shales. The top below the Llombera beds is visible at La Cueta section as a wavy surface downcutting ferrruginous hardgrounds of the top of the member (sb4, Fig. 5). At Meroy sb4 is a sharp, planar erosive surface with ferruginous mineralisation downcutting the Gordón strata (Fig. 6). In section Lumajo the upper boundary is not exposed.

The Lumajo section in the southwest starts with grey–brown pure shales (30 m) grading upward to bioturbated siltstones (10 m) and sandy limestones (6 m), and the upper half consists of cross-bedded very fine-grained sandstone

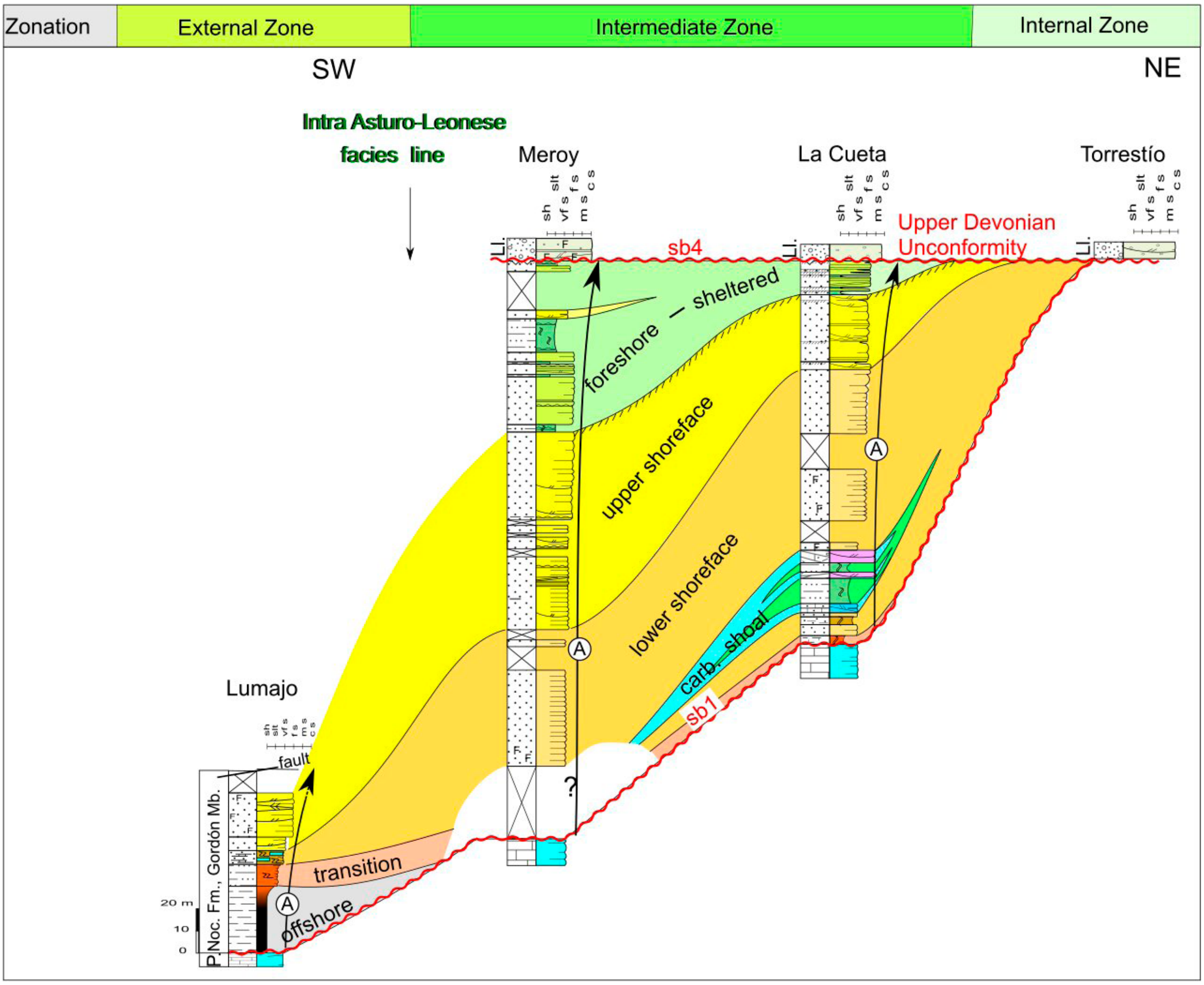

Figure 4. Facies zones and lithology of the Nocedo Formation, Gordón Member, in de Sil area. For legend, see Figure 3.

Figura 4. Zonas de facies y litología de la Formación Nocedo, Miembro Gordón, en el área de Sil. Para ver la leyenda, consulte la Figura 3.

topped by poorly exposed ferruginous, cross-bedded fine-grained sandstone with trough cross-bedding and herringbone structures (26 m). The upper part of the section is badly exposed and cut off by a fault. The sections of Meroy and La Cueta resemble each other closely, although the La Cueta section displays a thinner succession. The basal shale unit of the Lumajo section is missing, and at the La Cueta section the Gordón Member starts with a thin calcareous siltstone package grading upward to shale (4 m). Above, red ferruginous very fine to fine-grained sandstone and siltstone with calcareous intercalations occur (36 m), overlain by ferruginous very-fine grained sandstone (15–49 m) and grey sandstone (32–33 m), followed by light grey, fine-grained, cross-bedded sandstone (33–97 m). The upper part of the Gordón Member consists of parallel- and low-angle cross-laminated fine-grained sandstone with mud flaser bedding, and thin ripple-laminated intercalations of grey–brown or purple coloured shale–siltstone beds with sand lenses, local erosion surfaces and ferruginous mineralisation surfaces (16–78 m) (Fig. 7). Soft sediment deformation structures developed at the sandstone–mudstone contacts (Fig. 8).

Interpretation: The Gordón Member starts with a thick shale interval, which at some places overlies a thin basal fining-upward siltstone unit, and an overlying thick, coarsening- and shallowing-upward package (Van Loevezijn &

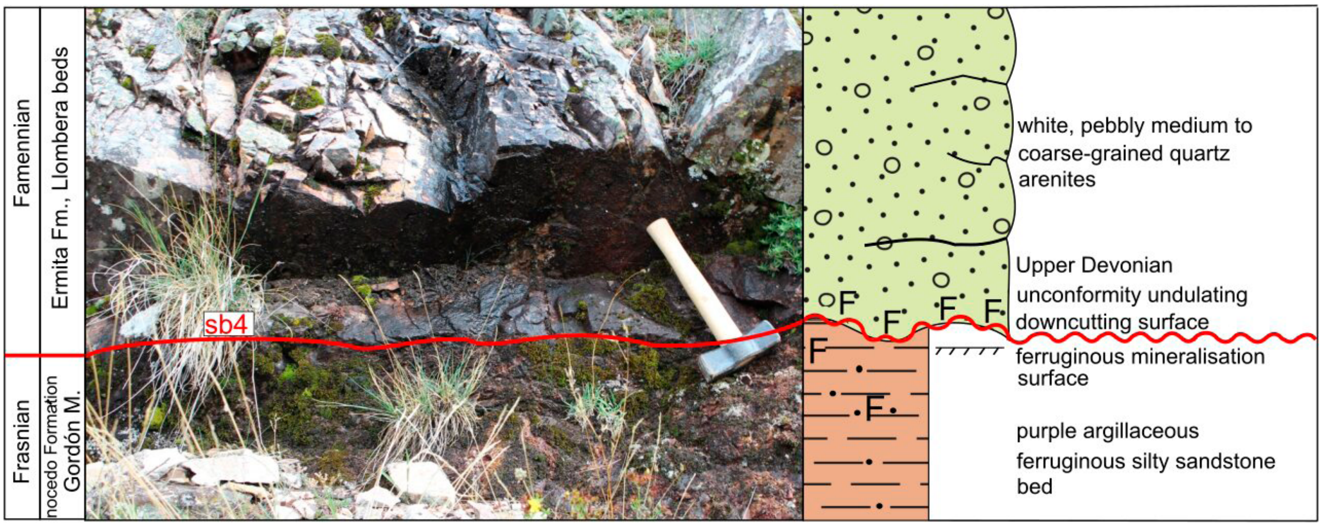

Figure 5. The Upper Devonian Unconformity (sb4) in the La Cueta syncline between the Gordón Member and the Llombera beds. The unconformity is a wavy erosive surface characterized by erosion and ferruginous mineralization. Hammer for scale.

Figura 5. Discordancia del Devónico Superior (sb4) en el sinclinal de La Cueta entre el Miembro Gordón y las capas de Llombera. La discordancia es una superficie erosiva ondulada caracterizada por erosión y mineralización ferruginosa. Martillo para escala.

Raven, 2021). The Lumajo section displays a trend from offshore mudstones (FT10) through offshore–transition silts (FT9), to sandy coastal deposits (FT8, FT3). The successions of Meroy and La Cueta displays a thin fining-upward succession of transitional–offshore fines (FT9), and an overlying trend from bioturbated silty sandstone and ferruginous very fine-grained sandstones with limestone intercalations of the lower shoreface facies (FT 7 and 8) and carbonate shoal association (FT4, FT 5, FT6), to cross-bedded sandstones of the upper shoreface association (FT3), to laminated foreshore sandstones (FT2) and silty deposits of the shallow-marine sheltered environment (FT1). The laminated silt and shale intercalations of the foreshore and sheltered coastal area, contain mottled crusts and strata-bounded bioturbated, laterally persistent, ferruginous, mineralization surfaces with ripple laminations, formed by periodical subaerial exposure of muddy sheltered coastal areas (Van den Bosch, 1969; Van Loevezijn, 1986). These surfaces are mainly developed in the foreshore sandstones of the northeastern sections (Intermediate Zone), close to the core area of the Cantabrian Zone. They represent non-deposition or erosion events of the shallow marine coastal area (Van Loevezijn & Raven 2021).

3.2. Sections Bernesga area

Description: The Gordón Member in the Bernesga area crops out in the Pedroso and Alba synclines, and is studied in the Beberino (77 m) and Vega de Gordón (72 m) sections of the Pedroso syncline, and in the Lombera (84 m), Huergas (306 m), Barrios (198 m), and Piedrasecha (98 m) sections of the Alba syncline (Fig. 1). It sharply overlies the light grey limestones of the Portilla Formation by means of sb1, which is visible at Beberino as an erosive surface downcutting the Portilla Formation (Van Staalduinen, 1973; Raven, 1983; Van Loevezijn & Raven, 2020). Elsewhere, sb1 consists of a sharp, flat surface. At Beberino and Vega de Gordón the member is overlain by the Llombera beds, separated by a sharp, plane, erosive surface (sb4). In the sections of the Alba syncline the member is overlain by shales of the Millar Member by means of sb2, represented by a flat surface.

The base of the Gordón Member at Beberino consists of grey-brown coloured, discontinuous wavy bedded, very bioturbated, very fine to fine-grained, calcareous sandstone with ripple lamination, 38 m thick, followed by a purple coloured, ferruginous, sandy, very coarse bioclastic limestone unit, 8 m thick. Above, purple coloured ferruginous, bioturbated, fine-grained sandstone, with erosive surfaces occur (17 m). The uppermost 14 m consists of light grey, medium-grained sandstone with low angle cross-lamination, banded ferruginous mineralisations and erosion surfaces. The Vega de Gordón section in the Pedroso syncline is very similar but slightly thinner.

Based on thickness and lithology, the sections of the Gordón Member in the Alba syncline can be grouped in eastern, central, and southwestern sections. The thin, sandy Llombera succession of the eastern area consists of calcareous bioturbated sandstones and cross-bedded quartz arenites (55 m), overlain by bioturbated shaly limestones and cross-bedded sandy bioclastic limestones (25 m) and a thin sandstone bed (3.75 m) (Fig. 9). The thick succession in the central part is visible at Huergas and Barrios (Fig. 13), with a basal shale and siltstone unit (15–42 m), a thick bioturbated sandstone unit (120–125 m), a cross-bedded quartz arenite with limestone intercalations (35–85 m), overlain by silty sandstones and limestones (85 m). Further southward the member gradually becomes thinner again (91–98 m) and very shaly (section Piedrasecha; Fig. 9).

Interpretation: The Gordón Member of the Pedroso syncline is interpreted as a siliciclastic shallow marine sheltered succession (FT1) with high energy carbonate shoal intercalations (FT's 4, 6), overlain by ferruginous fine-grained sandstones of the shoreface (FT's 3, 7). The

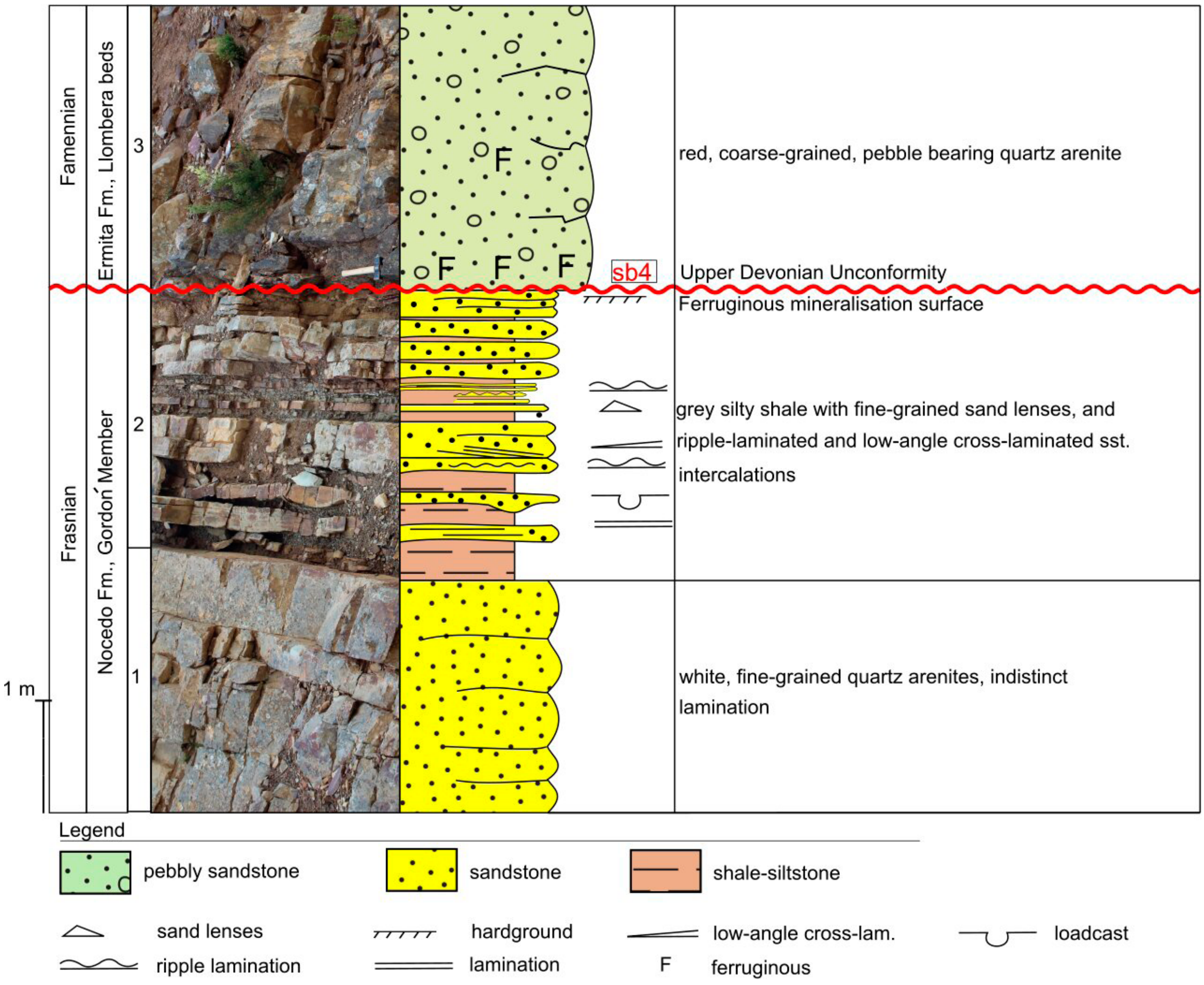

Figure 6. Upper Devonian Unconformity (sb4) in the Meroy section, between the Gordón Member and the Llombera beds. The unconformity is characterized by ferruginous mineralization and erosion. Hammer for scale.

Figura 6. Discordancia del Devónico Superior (sb4) en el tramo Meroy, entre el Miembro Gordón y las capas de Llombera. La discordancia se caracteriza por mineralización ferruginosa y erosión. Martillo para escala.

medium-grained, even- and low-angle cross-laminated sandstones in the uppermost part of the member (FT2), were deposited in the foreshore zone with swash and back-swash activity (Reineck & Singh, 1975; Nichols, 2009). Periodic subaerial exposure and erosion events are indicated by ferruginous banded horizons and truncation surfaces (Sanchez de la Torre, 1977; Van den Bosch, 1969; Loevezijn, 1986). The basal metres of the shale and siltstone succession (FT9, FT10) in the Alba syncline define a fining upward sequence that onlaps sb1 (Van Loevezijn & Van Loevezijn Peña, 2017). Above, the coarsening- and shallowing-upward succession of the Gordón Member to shallow marine environments occurs, without major deepening events (Fig. 9); from offshore shales (FT10), to offshore–transition siltstones (FT 9), to coastal shoreface sands (FT's 8, 7, 3, 2) with carbonate shoal intercalations (FT's 4, 5, 6).

4. Tectonic considerations

4.1. Variscan deformation

The Cantabrian Zone is an arc-shaped Variscan foreland fold-and-thrust belt, also known as the Cantabrian Orocline, formed during

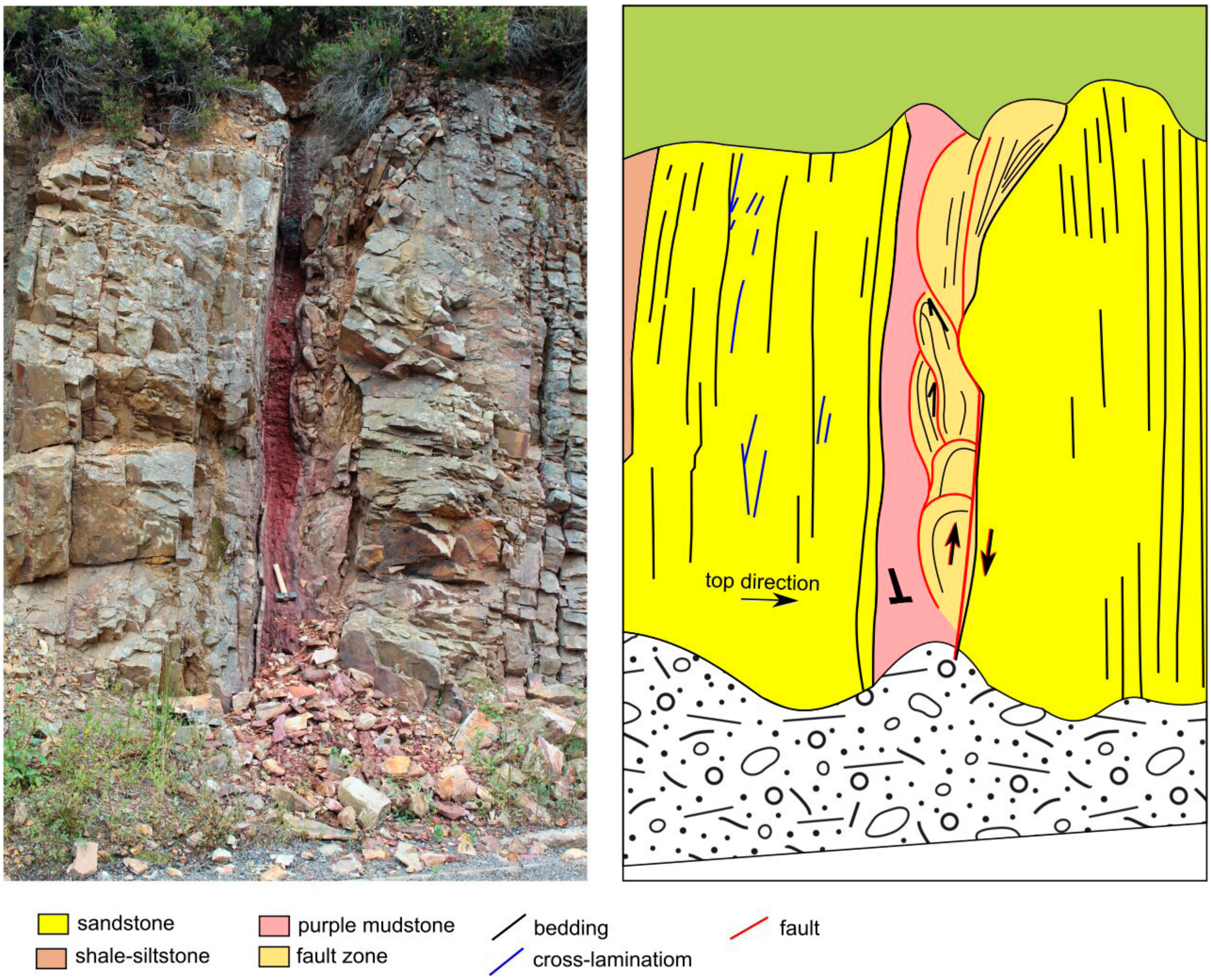

Figure 7. Purple coloured ferruginous mudstone bed, Meroy section, Gordón Member, indicating subaerial exposure and pedogenesis of the shallow-marine environment (Van Loevezijn, 1986). The mudstone bed acted as a mechanically weak layer where some minor flexural slip faults formed. Hammer for scale.

Figura 7. Capa de lutitas ferruginosas de color púrpura, sección Meroy, Miembro Gordón, que indica exposición subaérea y pedogénesis en un ambiente marino poco profundo (Van Loevezijn, 1986). La capa de lutita actuó como un nivel mecánicamente débil donde se formaron algunas fallas menores de deslizamiento por flexión. Martillo para escala.

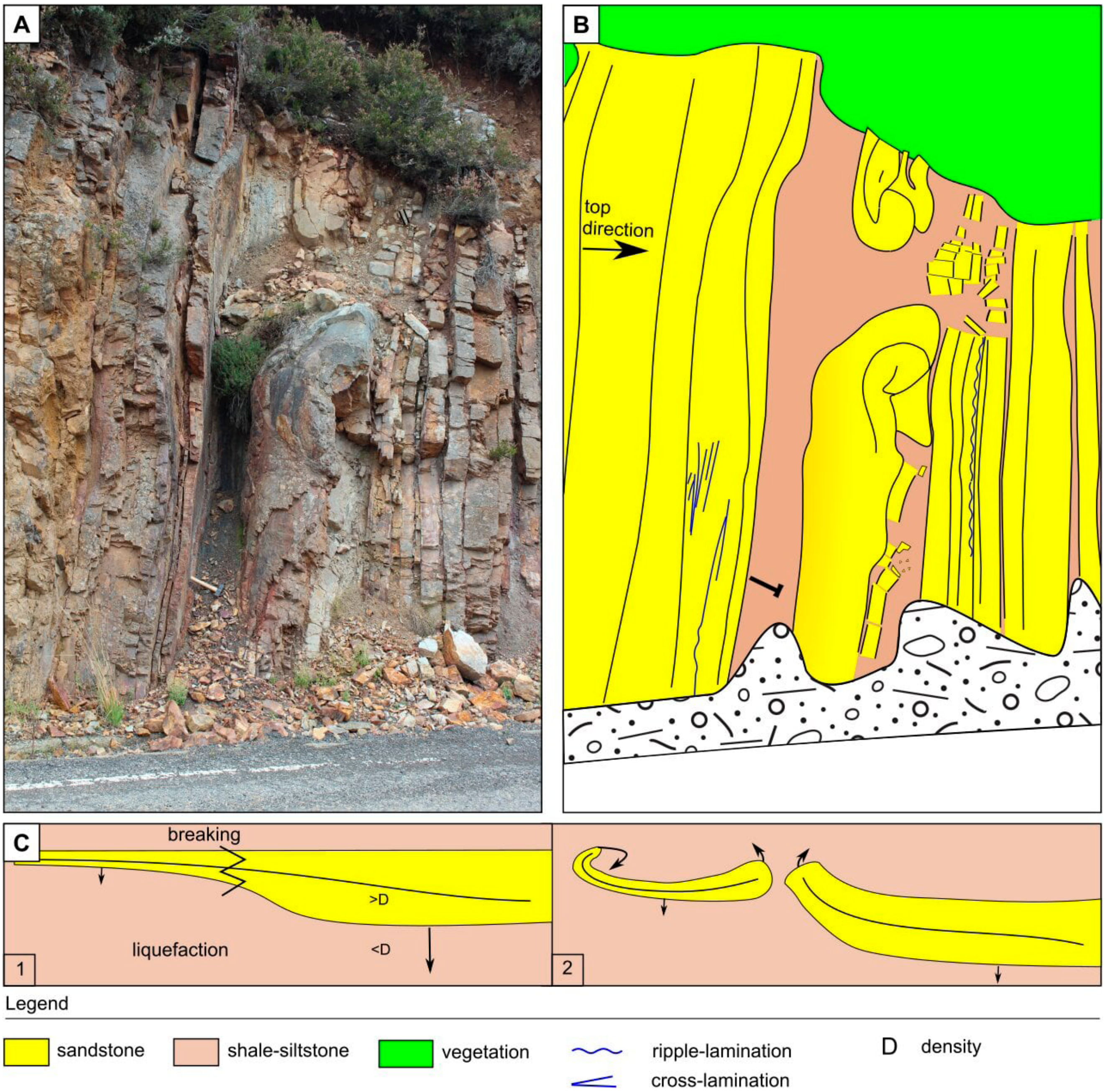

Figure 8. Deformed beds indicating plastic behaviour (liquefaction), Meroy section, Gordón Member. A) Photograph. B) Interpretation. Soft sediment deformation structures resulted from uneven overloading of a thick sandstone bed, probably a channel-fill in a mud matrix which thins out laterally. C) Genetic scheme: 1) Initial thick sandstone channel-fill succession 2) Sinking, breaking and up-curling of the sand segments. Arrow in B marks way up.

Figura 8. Capas deformadas que indican comportamiento plástico (licuefacción), sección Meroy, Miembro Gordón. A) Fotografía. B) Interpretación. Las estructuras de deformación de sedimentos blandos resultaron de la sobrecarga desigual de un lecho grueso de arenisca, probablemente un relleno de canal en una matriz de fango que se adelgaza lateralmente. C) Esquema genético: 1) Sucesión inicial de relleno de canales de arenisca gruesa 2) Hundimiento, rotura y curvatura de los segmentos de arena. La flecha en B apunta al techo.

the closure of the Rheic Ocean and the collision between Laurasia Gondwana, and microplates of Perigondwana. The Cantabrian orocline formation occurred during two major phases of the Variscan deformation (Gutiérrez-Alonso *et al.,* 2004; Weil, 2006). The result is reflected in the fold-and-thrust units of the Cantabrian Zone (Fig. 10). Therefore, the palinspastic reconstruction of the lateral extent of the Gordón Member is difficult. However, the general

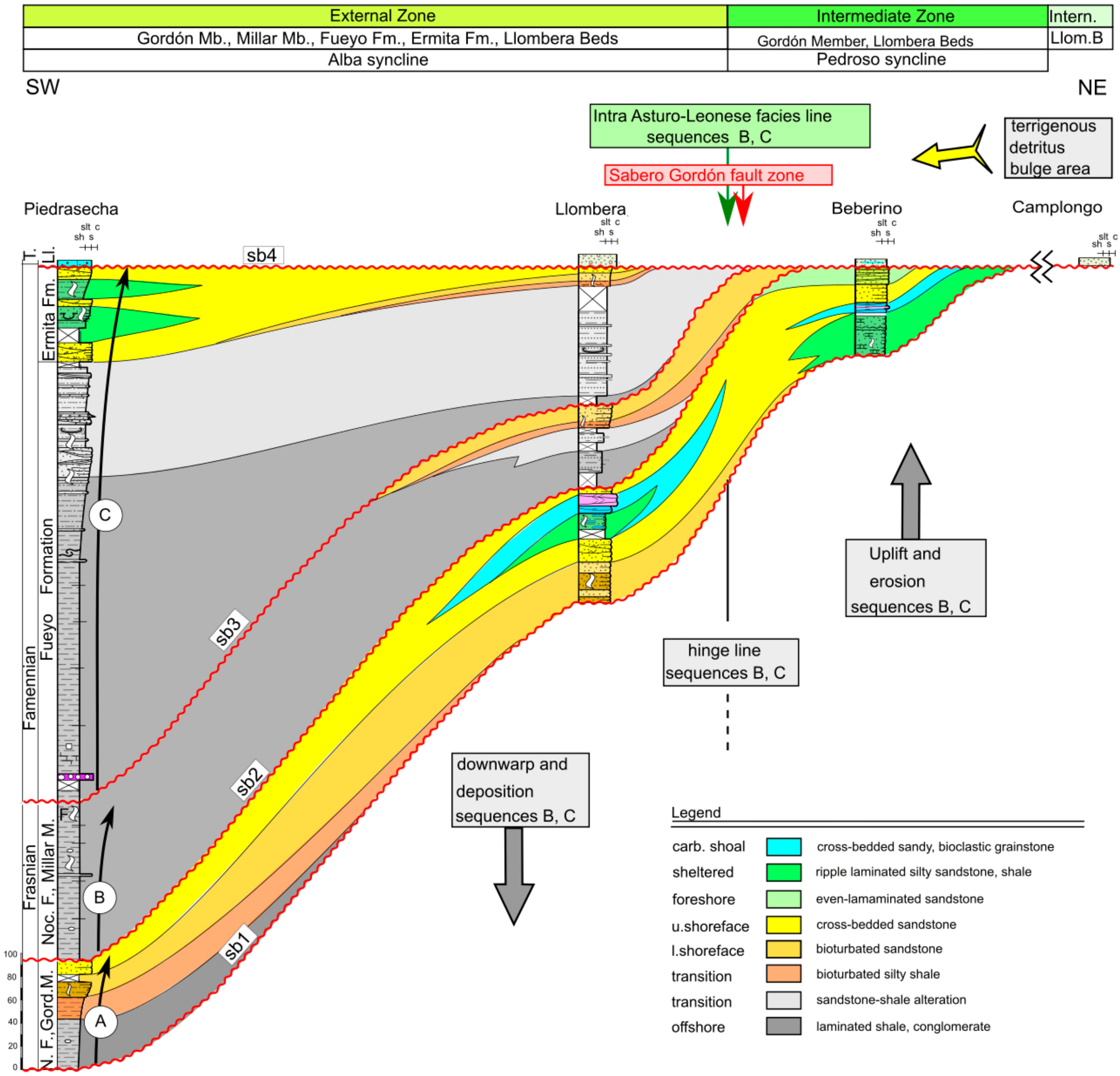

Figure 9. Clastic wedges of the Gordón Member, Millar Member, Fueyo Formation and Ermita Formation, with the position of the Intra Asturo–Leonese facies line between the sections of the Alba and Pedroso synclines indicated. Note the wide facies belts of sequence A, and the steep stratigraphic prisms of sequences B and C, bounded by the Intra Asturo–Leonese facies line.

Figura 9. Cuñas clásticas del Miembro Gordón, Miembro Millar, Formación Fueyo y Formación Ermita, indicando la posición de la línea de facies Intra Astur-Leonesa entre los tramos de los sinclinales de Alba y Pedroso. Nótense los amplios cinturones de facies de la secuencia A y los prismas estratigráficos verticales de las secuencias B y C, delimitados por la línea de facies Intra Astur-Leonesa.

absence of metamorphism and cleavage, and the low amount of internal strain (Peréz-Estaún *et al.,* 1988), points to deformation under shallow crustal conditions, and allows the realization of balanced cross-sections.

4.2. Palinspastic restoration

An attempt of an approximate palinspastic restoration was accomplished for the Alba and Pedroso synclines from a cross-section of the southern part of the Somiedo–Correcilla tectonic unit (Fig. 10) (Van Staalduinen, 1973);

north of the Pedroso syncline the Gordón Member is absent. The section is approximately parallel to the NNE directed Variscan tectonic nappe transport (Veselovski, 2004; Alonso *et al*., 2009). The palinspastic restoration accounts for folding and thrust displacement, to get an estimation of the actual original width of the studied area (Fig. 11). The restoration shows an original extent of about 5.5 km, and a tectonic shortening of the original extension of about 41%, which is less than the total of 70% tectonic shortening calculated for the Cantabrian Zone (Pérez-Estaún *et al*., 1988). The retro-deformed reconstruction of the Alba syncline is 8.5 km wide, separated by a tectonically removed anticlinal structure (1.5 km) from the 3.5 km wide Pedroso syncline.

5. The new reconstruction

The palinspastic restoration is useful to assess the original width of the shelf area, the original relative locations of sections, and the facies architecture. The displacement by thrusts and folds emphasizes the proximal–distal north–south Devonian facies trend, bringing rocks together, which were originally further apart (Fig. 12). The tectonic shortening highlights the Devonian facies differences between the thick, distal Upper Devonian facies successions of the Alba syncline and the thin, proximal, Upper Devonian facies successions of the Pedroso syncline, as the transitional area in between has been tectonically removed. The sections of the core of the Sil area are located in the Intermediate Zone close to the Intra Asturo–Leonese facies

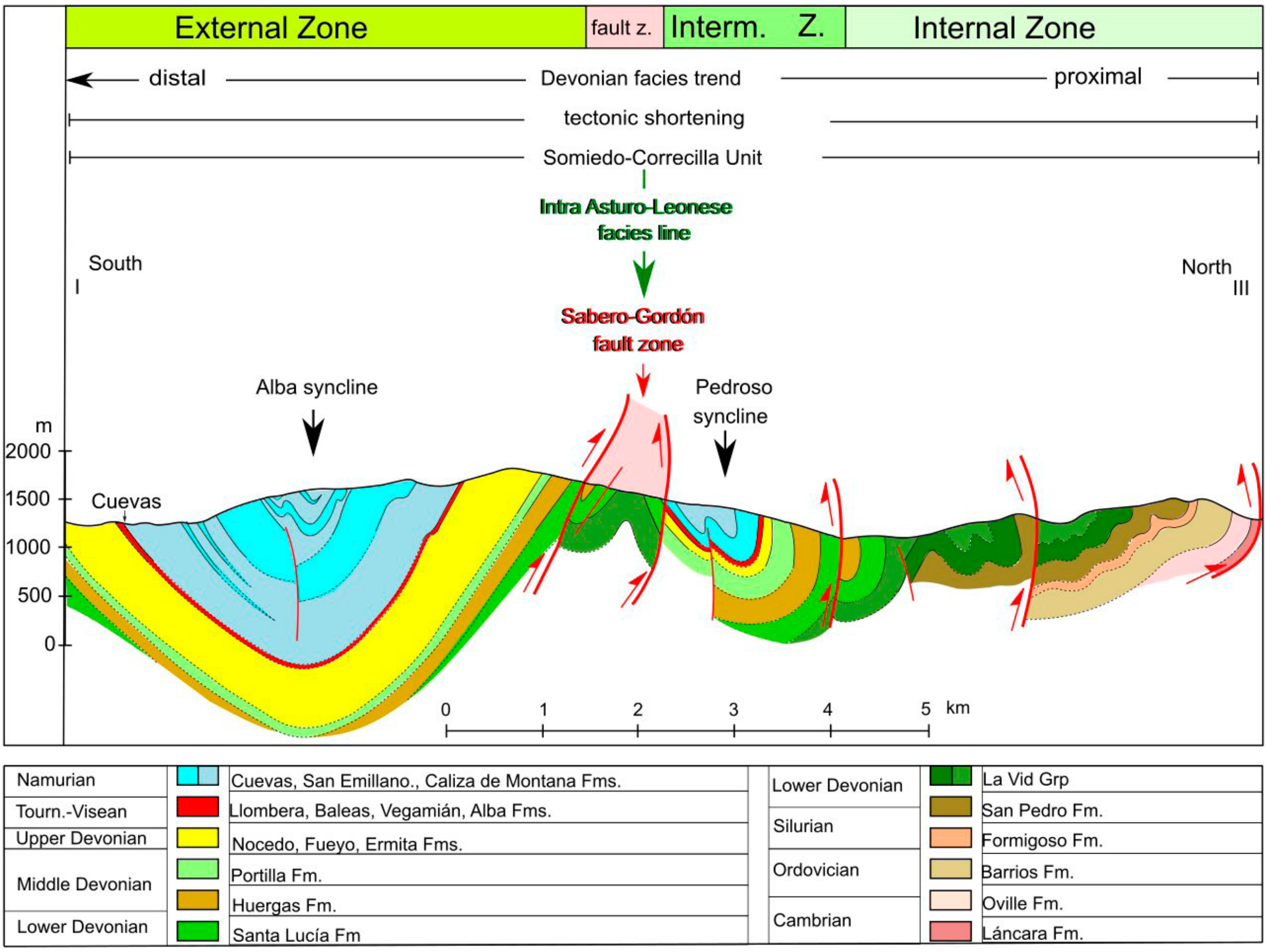

Figure 10. Structural N-S cross section of the Bernesga area with Devonian facies trends, tectonic shortening by thrusts, fold, and fault zones indicated. Modified after Van Staalduinen (1973).

Figura 10. Corte transversal N-S del área de Bernesga indicando las tendencias de facies Devónicas, el acortamiento tectónico por cabalgamientos, pliegues y zonas de falla. Modificado de Van Staalduinen (1973).

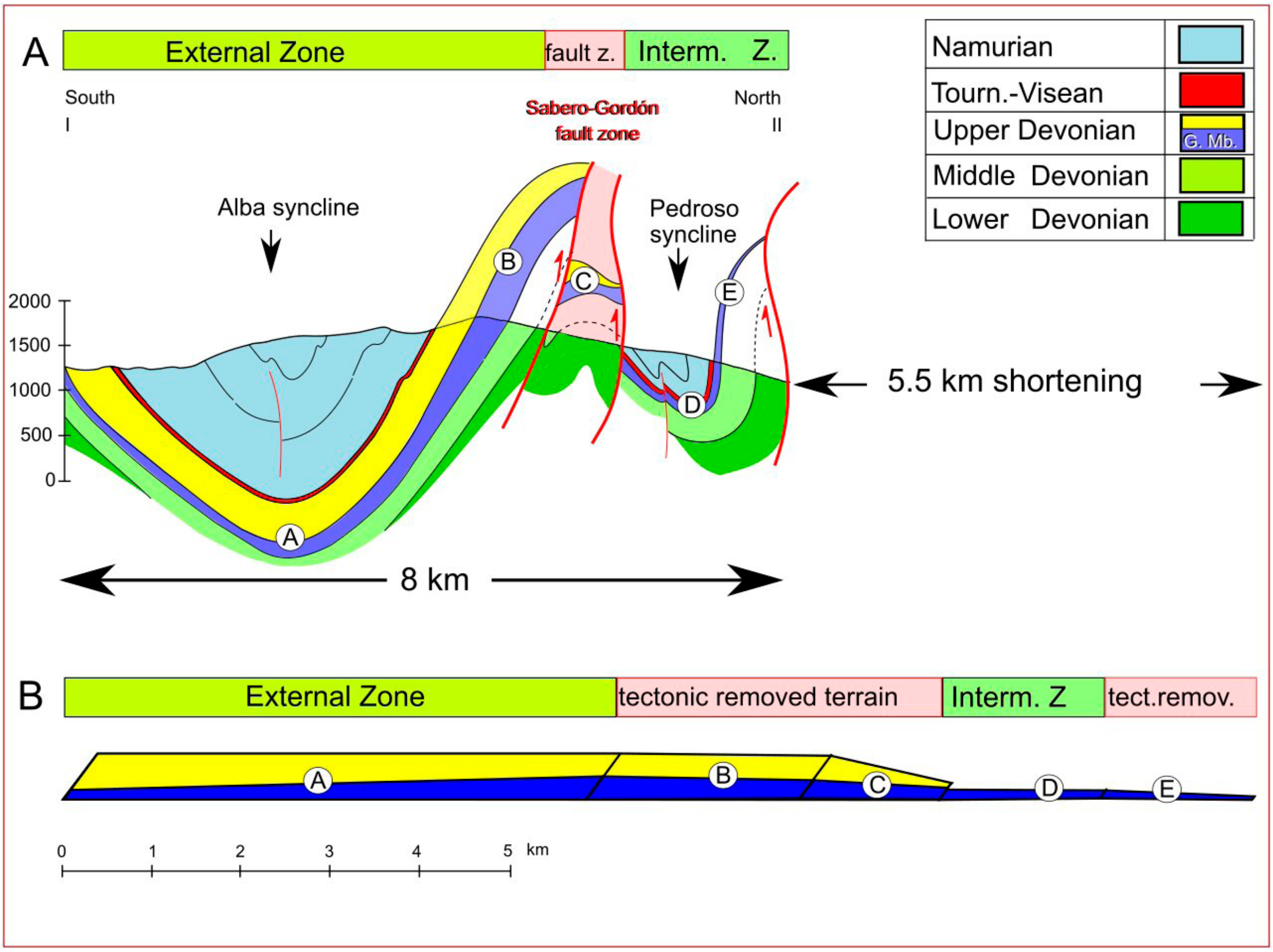

Figure 11. Palinspastic reconstruction of the southern part of the Somiedo–Correcilla unit. A) balanced cross section based on Van Staalduinen (1973) (G. Mb.= Gordón Member). B) Upper Devonian restored primary extension.

Figura 11. Reconstrucción palinspástica de la parte sur de la unidad de Somiedo–Correcilla. A) sección transversal balanceada basada en Van Staalduinen (1973) (G. Mb.= Miembro Gordón). B) Extensión inicial restituida para el Devónico superior.

line. There, the Upper Devonian succession displays a thickness intermediate between sections of the Pedroso (thinner) and Alba (thicker) synclines. Being thicker, they have the same stratigraphic architecture as the Pedroso sections ending with sandy coastal deposits truncated by the Upper Devonian Unconformity, and fit the general facies scheme between the synclines. Thus, considering their locations in the Intermediate Zone, their stratigraphic architecture, and their thickness, the Meroy and La Cueta sections, could represent (part of) the missing area between the Alba and Pedroso synclines. In Figure 13, the Sil sections of Meroy and La Cueta are included in the north–south transect of the Bernesga area. Thus, instead of the steep gradient of facies change from a thin proximal succession in the north to a nearby thick southern succession (Sánchez de la Torre, 1977; Sánchez de la Torre *et al.*, 1983), involving the so–called Intra Asturo–Leonese facies line in between (Van Loevezijn, 1983; Van Loevezijn & Raven, 1983; Raven, 1983; Van Loevezijn, 1986), a more gradual transition between the southern and northern successions occurs by restoring the primary extension of the depositional area, and to include the Sil sections in the Bernesga transect. These gradual thickness and facies transitions indicate that during deposition of the Gordón Member the Intra Asturo–Leonese Facies Line was probably not a supported paleogeographic feature.

6. Basin configuration

The Gordón Member starts with a thin, up to 20 m, fining upward sequence of shales and siltstones onlapping sb1, indicating the early Frasnian shoreline transgression against the Cantabrian Massif to the north. Above, and over a substantial time span, a thick coarsening upward succession was formed, as the available accommodation space was being filled by prograding coastal successions. The north-eastern sections, close to the massif, contain a thin, fine-grained succession of a sheltered environment. The depocentre of the basin was located in the central part, where a thick succession of shoreface sandstones was laid down, with coarse-grained carbonate shoal intercalations (Fig. 13). A ferruginous mineralisation surface separates these shoreface sandstones from the overlying bioturbated sandy siltstones with cross-laminated carbonate intercalations, indicative of low bottom energy conditions allowing deposition of fines in a shallow-marine zone sheltered by carbonate shoals. Towards the edge of the basin in the north, mottled ripple-laminated sandy shale, and laterally persistent, bioturbated, ferruginous, mineralization surfaces occur, representing non-deposition or erosion events in the coastal area of the proximal part of the basin. In the southernmost depositional area, where the bathymetrical centre of the basin was located, the thick sandstone package changes to a thin succession dominated by laminated shales and siltstones of the offshore facies.

7. Discussion

Balanced cross sections: A palinspastic restoration was accomplished for the Alba and

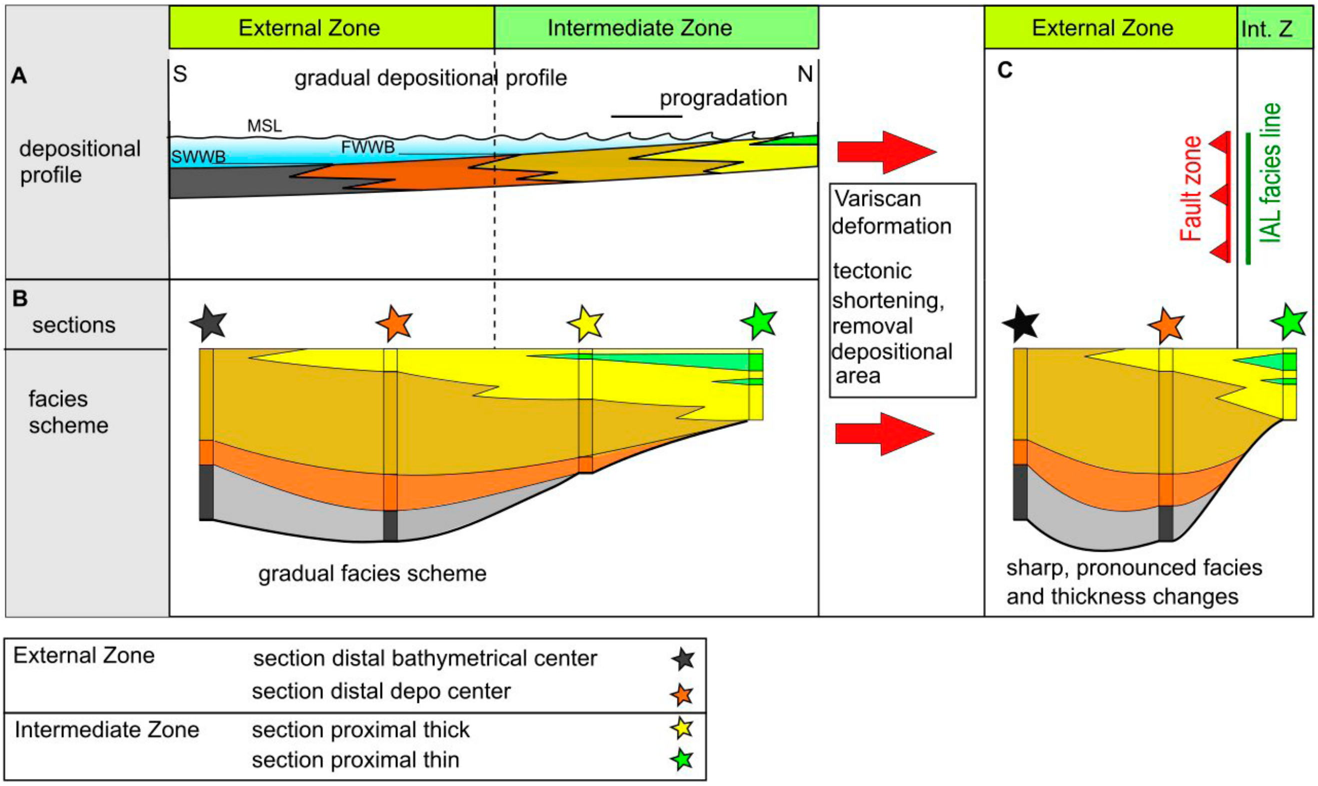

Figure 12. The displacement by the thrusts emphasizes the distal-proximal south-north Devonian facies trend, bringing rocks together, which were originally further apart. A) Depositional profile (MSL: mean sea level; FWWB: fair weather wave base; SWWB: stormy weather wave base). B) pre-Variscan N–S transect with extensive facies patterns. C) N–S transect after Variscan tectonic shortening, with large facies and thickness changes over short distances, as the transitional area in between is now tectonically removed.

Figura 12. El desplazamiento por los cabalgamientos enfatiza la tendencia sur-norte y distal-proximal de las facies del Devónico, acercando rocas que originalmente estaban más separadas. A) Perfil deposicional (MSL: nivel medio del mar; FWWB: base de olas de buen tiempo; SWWB: base de olas de tormenta). B) Corte N-S pre-varisco con patrones de facies. C) Corte N-S tras el acortamiento tectónico varisco, con grandes facies y cambios de espesor en distancias cortas, ya que el área de transición intermedia ha sido eliminada tectónicamente.

Pedroso synclines from a cross section of the southern part of the Somiedo–Correcilla unit. Estimates of tectonic shortening derived from balanced cross sections are widely used in paleogeographic reconstructions (*e.g.*, Woodward *et al*., 1989; McQuarrie & Van Hinsbergen, 2013; McPhee *et al.,* 20018). Although the restoration in this study is based on a firm dataset (the geological map of Van Staalduinen, 1973), the restoration is approximate, since not enough map-data are available to make a fully reliable construction. We have to realize that shortening by balanced cross sections deliver an estimated *minimum* value of the decreased horizontal width by folding and thrusting, as tectonic removal may lead to an underestimate of shortening in a reconstruction (McPhee *et al.,* 2018). Therefore, the actual extension of the restored terrain could be well over the calculated values.

Basin configuration: The restored facies architecture of the Gordón Member divides the Frasnian basin into three facies realms: the inner

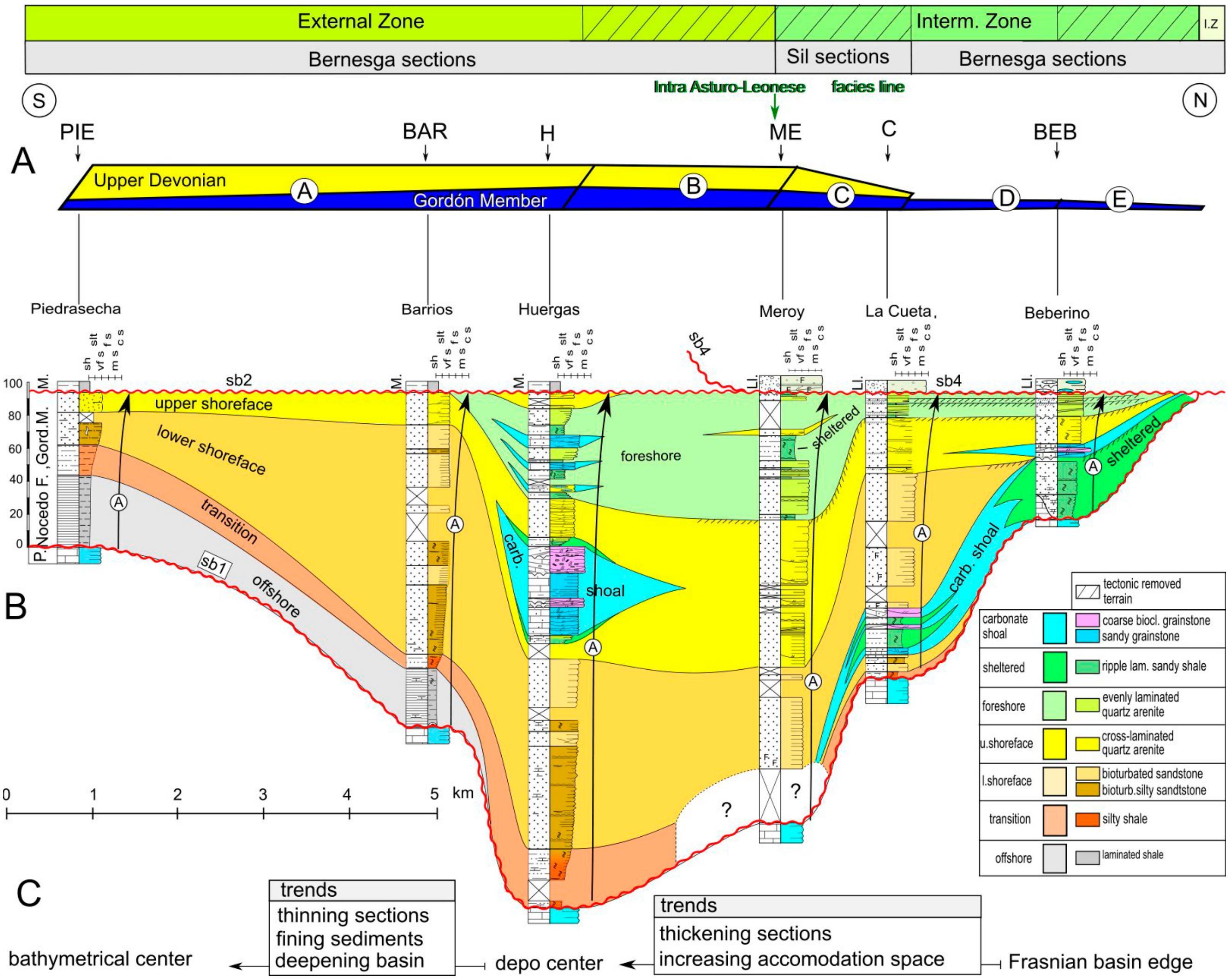

Figure 13. Interpretive north–south facies transect of the Gordón Member. A) Upper Devonian restored primary extension. B) North–south transect of the Gordón Member of the Bernesga area with the Sil sections between the External Zone and Intermediate Zones. Locations of sections are restored for thrusting and folding, resulting in more gradual facies and thickness changes. Unconformity surface top Gordón Member as reference level. C) Basin configuration trends. For explanation of symbols, see Figure 3.

Figura 13. Corte interpretativo de facies norte-sur del Miembro Gordón. A) Extensión primaria restaurada para el Devónico superior. B) Corte norte-sur del Miembro Gordón del área de Bernesga con los tramos del Sil entre la Zona Externa y la Zona Intermedia. Las ubicaciones de los cortes se restauran considerando los cabalgamientos y pliegues, lo que da como resultado cambios de facies y espesores más graduales. Superficie de discordancia del Miembro Gordón superior como nivel de referencia. C) Tendencias de configuración de la cuenca. Para obtener una explicación de los símbolos, consulte la Figura 3.

part, or basin edge, in the northeast contains thin fine-grained successions deposited in sheltered areas with intercalations of high-energy deposits, including carbonate shoals, and displaying erosional surfaces and hardgrounds. The successions in the central part of the basin consist of thick well-developed, prolonged, coarsening-upward successions with thick sandstone packages, indicating a shallowing upward from offshore–transition to foreshore environments. Finally, the southern sections of the outer part of the basin, are thin and characterized by well-developed shale successions, representing a distal environment away from the reach of the sandy coastal sediment supply.

Shallowing upward sequence: The gradual shallowing-upward succession of the Gordón Member is recorded in one prolonged coarsening-upward sequence. However, minor depth fluctuations do exist; sharp ferruginous surfaces of erosion and/or non-deposition can be correlated from the thin proximal successions in the north, into the thick successions in the central part of the basin (Fig. 13). Regressive trends in sea-level and/or tectonic pulses resulted in transient (partial) emersion and subaerial exposure of the (northern) edge of the basin.

The Intra Asturo-Leonese Facies Line: Sequence A of the Gordón Member extends far into the Asturo–Leonese facies area, covering the outer and central basin part (External Zone) and the inner basin part (Intermediate Zone) (Fig. 1), with gradual thickness and facies transitions between the palinspastic restored distal southern and proximal northern successions. The model of a southward sloping Upper Devonian depositional system with steep facies changes (Sánchez de la Torre, 1977; Van Loevezijn, 1983; Van Loevezijn & Raven, 1983; Raven, 1983; Sánchez de la Torre et al., 1983; Van Loevezijn, 1986) is (partly) contrary to the palinspastically restored model proposed in this study, with gradual lateral thickness changes and wide facies belts. The gradual facies change is also contrary to the concept of an Intra Asturo–Leonese Facies Line, and the influence of this facies line on the depositional pattern of the Gordón Member was negligible. In the overlying Upper Devonian sequences B (Millar Member), and C, (Fueyo and Ermita Formations) however, it is a valid palaeogeographic feature, controlling the steep facies and thickness distribution patterns of the narrow External Zone (Fig. 9) (Van Loevezijn, 2020). Therefore, the Upper Devonian succession of sequences A, B, and C may indicate the evolution of the Upper Devonian transect from wide depositional facies belts in sequence A (Gordón Member), towards steep, narrow, depositional profiles in sequences B and C.

8. Conclusions

A tectonic shortening by thrusts and folds in the southern part of the Somiedo–Correcilla Unit of 41% is assumed. The sections of the Sil and Bernesga areas correlate well, and the Gordón Member transect shows a consistent facies pattern. The restored primary extension of the Gordón strata indicates a depositional area, extending far into the inner part of the Asturo–Leonese facies area, with thin truncated successions in the northeast, thick coastal sand successions in the centre, and thin offshore successions in the southwestern distal part. The Gordón Member was deposited on a gentle depositional slope as is demonstrated by its facies architecture, showing a gradual shallowing upward succession with wide facies belts.

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