sciendo

Geologos 29, 2 (2023): 77–97
https://doi.org/10.14746/logos.2023.29.2.09

GEOLOGOS

Pre-Variscan palaeogeographical structures in the Cantabrian Zone, Spain: some critical considerations regarding their origin, location and significance

Gerard B.S. van Loevezijn

Jan Sluijtersstraat 7, 3443 HP Woerden, the Netherlands
e-mail:stratpal.ger@gmail.com

Abstract

An update of the main Devonian pre-Variscan palaeogeographical features of the southern Cantabrian Zone is presented. The approximal locations of these features are recorded in sections studied, with thin, incomplete developments for the highs and thick successions for the troughs. Generally, pre-Variscan palaeogeographical features were affected by Variscan and Alpine orogenic deformations, but with a different impact. Oroclinal bending, tectonic shortening by thrusts, movements along strike-slip faults and bending by folds all affected the Devonian palaeogeographical features, and only an approximation of their location and shape can be given. Nevertheless, the palaeogeography recorded in pre-Variscan sedimentary successions and their relative positions, provide specific, clear and objective evidence of the pre-Variscan elements.

Key words: Devonian, palaeogeography, Variscan orogeny, Alpine deformations

1. Introduction

The Cantabrian Zone (abbreviated henceforth as CZ) is the northern external thrust-and-fold belt of the Variscan Iberian orogen (Matte, 1991; Díez Fernández et al., 2016). It contains one of the best-preserved and best-exposed, non-metamorphic to anchimetamorphic sedimentary records of the northern Gondwana continent, ranging in age from Ediacaran to Permian (Fig. 1A). It displays variations in thickness and facies that reflect a complex basin history and configurations (Van Loevezijn, 1986; Keller et al., 1988; Vera de La Puente, 1989; Aramburu et al., 1992; Van Loevezijn & Raven, 2020). Pre-Variscan palaeogeographical features are generally affected by Variscan and Alpine orogenic deformations, but with a different impact. Many pre-Variscan palaeogeographical elements, defined by Dutch scientists as facies change lines and palaeohighs of the southern CZ were developed in the 1960s and 1970s (e.g., Sitter, 1962; Brouwer, 1964; Evers, 1967; Van Adrichem Boogaert, 1967; Reijers, 1972; Raven, 1983; Van Loevezijn, 1983). Since then, geological knowledge has increased and earlier interpretations should be reassessed critically and updated. Disagreement and discrepancies exist regarding extent, location, age or even existence of pre-Variscan palaeogeographical features of the CZ (e.g., Alonso et al., 1991; Nijman & Savage, 1991; Fernández et al., 2006).

The recognition of pre-Variscan palaeogeographical elements must be based on features of the pre-Variscan Palaeozoic successions after restoring the overprint by Variscan deformation, represented mainly by thrust shortening of variable magnitude. The fact that the pre-Variscan succession is deformed by Variscan and Alpine structures, some of which might actually be reactivated pre-Variscan structures, has led to disagreement over some of the interpreted pre-Variscan palaeogeographical elements discussed herein. There is an ongoing debate on the role of the bounding faults during pre-Variscan sedimentation (Kullmann & Schönenberg, 1975; Marcos, 1979; Nijman & Savage, 1991; Alonso et al., 1991, 2009; Espina et al., 1996). Some authors claim that the Variscan deformation has not been satisfactorily accounted for, in such way that the facies changes observed can be merely an effect of Variscan shortening (Fernández et al., 2006). In the present paper, objective, specific evidence of these interpreted pre-Variscan palaeogeographical elements is provided.

Thus, although there is no agreement over the extent and shape of pre-Variscan palaeogeography, the existence of the features must be recorded in pre-Variscan successions and their facies distribution patterns. Here, some of the main (supposed) pre-Variscan palaeogeographical units of the southern CZ, their origin, stratigraphical expression, relative locations and assumed roles during pre-Variscan times are investigated.

2. Geological settings

2.1. The Cantabrian Zone

The Iberian Massif of Lotze (1945) represents a fragment of the Variscan Orogen (Fig. 1A). It forms the major part of the Ibero-Armorican chain. It displays an arcuate shape and is related to the closure of the Rheic Ocean and the collision between Laurussia and Gondwana (see Lotze, 1945; Ribeiro et al., 1990; Pastor-Galán et al., 2013). The orocline of the CZ formed during two major phases of Variscan deformation. The originally N–S-directed linear belt was affected primarily by E–W compressional events at the end of the Carboniferous, creating large thrust zones and tectonic shortening. A subsequent change to a N–S-directed compression bent the thrust zones, and was responsible for most of the Asturian Arc curvature, resulting in the finite orocline arc shape during the Early Permian (Weil, 2006; Wotte, 2009; Weil et al., 2013).

The CZ represents the external zone of the Iberian Variscan orogen (Lotze, 1945; Matte, 1991; Pérez-Estaún & Bea, 2004; Gutiérrez-Alonso et al., 2015), and is a classic foreland fold-and-thrust belt characterised by thin-skinned tectonics with a transport direction towards the core of the arc (Julivert, 1971) (Fig. 1B). During Alpine orogeny, the CZ was uplifted and exhumed with little internal deformation of the uplifted block (Alonso et al., 1996; Fillon et al., 2016).

To the west, the Narcea Antiform separates the western nappes of the CZ from the West Asturian-Leonese Zone (henceforth abbreviated as WALZ), a more internal unit of the Iberian Massif

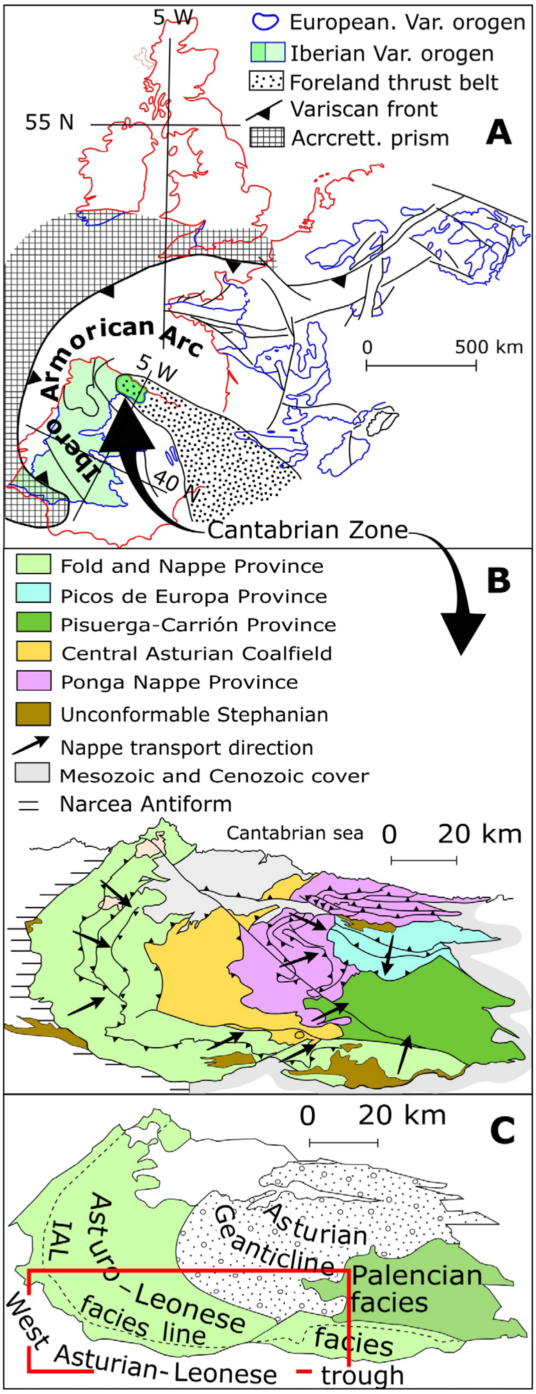

Fig. 1. Location and tectonostratigraphical units of the Cantabrian Zone in north-west Spain. **A** – Location of the Cantabrian Zone (CZ) between the pieces of the Variscan Orogen of western Europe (modified after Alonso et al., 2009); **B** – Tectonostratigraphical units of the CZ (after Julivert, 1971); **C** – Main Devonian palaeogeographical units of the CZ and the location of the West Asturian-Leonese trough. Red rectangle indicates study area shown in Figure 6.

(Gutiérrez-Alonso, 1996; Keller et al., 2007) (Fig. 1). To the north the CZ is bounded by the Bay of Biscay, and eastwards and southwards the zone is covered by Mesozoic and Cenozoic deposits (Gallastegui et al., 2016).

The CZ has been subdivided into several geological regions on the basis of stratigraphical and structural features (Julivert, 1971), which have subsequently been slightly modified (Pérez-Estaún et al., 1988; Rodríguez-Fernández & Heredia, 1988; Alonso et al., 2009) (Fig. 1B). The Silurian-Devonian rocks in the CZ occur mainly in the geological regions of the Fold and Nappe Province and the Pisuerga-Carrión Province, where they consist of the Asturo-Leonese and the Palencian facies of Brouwer (1964), respectively (Fig. 1C). These two tectonostratigraphical regions of the CZ host the study area.

2.2. Palaeozoic succession

The Palaeozoic succession of the CZ has been divided classically into a pre-, syn- and post-orogenic unit (Marcos & Pulgar, 1982; Julivert, 1978). To these, a transition unit (Van Loevezijn, 2020) and an early syn-orogenic unit (Alonso et al., 2015) should be added.

Pre-orogenic succession. The onset of the Palaeozoic is characterised by rift-related igneous activity and the presence of a widespread angular unconformity that records deformation in Ediacaran rocks (Pereira et al., 2012). The Cambrian to Devonian, pre-orogenic succession consists of siliciclastics and carbonates that are interpreted to have been deposited on extensive, stable platforms of large epicontinental inland seas on the northern passive margin of Gondwana (e.g., Aramburu et al., 2002; Pastor Galán et al., 2013; Stampfli et al., 2013; Gutiérrez-Alonso et al., 2015 and references therein). This passive margin was subjected to additional extension and deposition of rift-related successions during the Middle to Late Ordovician (Navidad et al., 2018). The Devonian basin was fed from an emerged land area, the Asturian Geanticline of Van Adrichem Boogaert (1967), located to the north-east of the Devonian basin in the CZ core area (Raven, 1983; Hofmann & Keller, 2006). The land area is characterised by a near-complete absence of Silurian and Devonian deposits. The Devonian proximal-distal facies trend from the CZ core towards the outer areas was modified by small palaeogeographical features, that is, the Somiedo High in the west and the Pardomino High between the Bernesga and Esla areas (Evers, 1967; Raven, 1983; Van Loevezijn, 1986; Keller et al., 1988).

The CZ contains an up-to-2,000-m-thick Devonian shelf succession consisting mainly of coarse-grained siliciclastics with reef intercalations: the Asturo-Leonese facies of Brouwer (1964). The outermost part of the facies area, or the External Zone, contains the most complete and thickest Silurian-Devonian succession (Raven, 1983; Van Loevezijn, 1986). In the Pisuerga-Carrion Province, nappes in a Carboniferous flysch succession contain an up-to-800-m-thick, fine-grained Silurian-Devonian pelagic succession of mainly dark shales and carbonate mudstones; this is the pelagic Palencian facies of Brouwer (1964). These Palencian facies have been interpreted as allochthonous, having been emplaced as gravitational nappes from the south of the CZ (Frankenfeld, 1983, 1984).

Transition succession. The first record of instability along the passive margin, owing to loading in the hinterland, was interpreted to have occurred in Late Devonian times by Keller et al. (2007). The Upper Devonian succession consists of sedimentary clastic wedges, deposited on the outermost rim of the CZ. According to Keller et al. (2007) and Van Loevezijn (2020) this would represent the initiation of Variscan orogeny, when the most external margin of the Gondwana continent was incorporated into a subduction zone (Abati et al., 2010; Díez Fernández et al., 2016).

Early syn-orogenic succession. The widespread Upper Devonian unconformity separates the Upper Devonian clastic wedges from the overlying condensed Mississippian sequence, approximately 30 m thick (Kullmann & Schönenberg, 1975; Colmenero et al., 2002; Keller et al., 2007). This records the inversion to a marginal basin influenced by the continuing Variscan collision taking place further west (see Colmenero et al., 2002; Gutiérrez-Alonso et al., 2015 and references therein), and is interpreted as an underfilled foreland basin succession, formed in absence of significant early orogenic relief (Keller et al., 2007; Van Loevezijn, 2020). It marks the fundamental reorganisation of depositional system to the Carboniferous sedimentation.

Syn-orogenic succession. The syn-orogenic foredeep fill succession contains the main part of the Carboniferous. The several thousand metres thick successions fill up the deep throughs in front of the approaching thrust units from the west (Colmenero et al., 2002). Sediment shedding from the approaching Variscan fold and thrust belt started during the Namurian, when debris flow deposits and turbidites are first observed in the most south-westerly part of the CZ (Reuther, 1977; Rodríguez-Fernández, 1993). These sediments are interpreted to originate from erosion of the internal zones of the Variscan Orogen in the south-west (Colmenero et al., 2002).

Post-orogenic succession. The post-orogenic successions are represented by discontinuous Stephanian-Lower Permian coal basins (Colmenero et. al., 2008; Martin-Meríno et al., 2014).

3. Pre-Variscan palaeogeography

3.1. Controlling mechanisms

A number of tectonic models on regional and local scales have been proposed for the controlling mechanism(s) of (pre-Variscan) palaeogeographical features. These include the following:

Flexural bending lithosphere. During Frasnian–Famennian times, the external margin of the Gondwana continent was incorporated into a subduction zone (Abati et al., 2010; Díez Fernández et al., 2016). The supra crustal load led to flexural bending of the lithosphere of Gondwana and produced a bulge in the CZ core area with uplift and erosion, and subsidence and prograding clastic wedge sedimentation in the outermost external part of the zone (Keller et al., 2007, 2008; Van Loevezijn, 2020).

Basement wrenching. A tectonic model in which major basement wrench faults account for subsidence and uplift areas and sedimentation directions has also been proposed. Wrench faulting can control sedimentation throughout Palaeozoic times (Reijers, 1985; Nijman & Savage, 1989, 1991; Keller, 1997), whereas Alonso et al. (1991) emphasised that most interpreted pre-Variscan palaeogeographical features did not result from basement wrenching, but instead could be attributed to Variscan deformation.

Local tectonism. Local tectonic movements can result in individualisation of palaeohighs and intervening areas (Stel, 1975; Raven, 1983; Hofmann & Keller, 2006), creating emerged landmasses that delivered sediment to neighbouring sedimentation areas.

Geological data do not point to a single process, and various controlling mechanisms may have acted simultaneously or successively. From Lower Devonian successions Fernández et al. (2006) and Keller (1997) concluded that tectonics must have played a significant role in the facies distribution and vertical organisation of these successions, and Van Loevezijn (2020) demonstrated that Upper Devonian uplift and erosion and nearby subsidence and deposition probably were tectonically controlled.

However, the present map-appearance of supposed pre-Variscan features of the CZ is that the pre-Variscan palaeogeography often crosses Variscan and later faults (e.g., see Fig. 6, the Pardomino High). Obviously, the shape of the old palaeogeography is affected by later Variscan thrusts and folds and only an approximation of its location and shape can be given. Nevertheless, the palaeogeography recorded in pre-Variscan sedimentary successions and their relative positions, provides specific, clear and objective evidence of pre-Variscan elements.

Thus, although there is no agreement over the controlling mechanisms or even over the existence of pre-Variscan palaeogeography and caution should be exercised over the identification of any potential structure, the thickness and facies distribution of Devonian successions makes it likely that tectonics played a significant role in sediment distribution.

3.2. Palaeogeographical challenges of/in the Cantabrian Zone

When taking Variscan deformation into account in pre-Variscan palaeogeographical reconstructions of the CZ, one should be aware of the following:

Kinematic model. The various kinematic models proposed for the formation of the arcuate shape of the Cantabrian Zone, favouring a late bending of an initial linear belt (Alonso et al., 2009; Weil et al., 2013), which disrupted and shifted to some extent the original pre-Variscan facies patterns. A palinspastically restored linear belt was proposed by Weil et al. (2013, their fig. 9) and Keller et al. (2007, their fig. 7) showed an idealised rendering of the relative linear position of thrust units prior to emplacement.

Tectonic shortening. The Palaeozoic succession of the CZ displays a well-developed, thin-skinned Variscan structure; the succession was deformed by a set of imbricated thrusts and by late high-angle faults. The strong tectonic shortening by the nappe displacement significantly modified the original palaeogeography, bringing together successions that originally lay far apart. The bent thrust units of the CZ resulted in a total tectonic shortening of about 70 per cent (Pérez-Estaún et al., 1988), with an accumulated displacement ranging from 90 km for the Esla Nappe (Alonso, 1987) to 150 km for the entire CZ, as calculated by Wotte (2009) on the basis of published data. Tectonic shortening contains thrust displacement directions in the southern CZ towards the north-east (Pérez-Estaún et al., 1988) (Fig. 1B). Devonian deposits of the Asturo-Leonese facies area in the southern CZ display a palaeogeographical trend from thicker and more distal successions in the south and west to thinner more proximal successions, with unconformities, to the north and north-east, that is, towards the core of the CZ (Van Adrichem Boogaert, 1967; Raven, 1983). Therefore, the general south-west/north-east Devonian facies trend is approximately parallel to the south-west/north-east tectonic shortening of the Palaeozoic thrust stack, and the displacement by the thrusts emphasises the distal-proximal facies trend, bringing together rocks that were originally further apart (Fig. 2).

Missing pieces of the puzzle. As a result of Variscan shortening, the present areal extent of the CZ represents only a small portion of a much larger original outcrop belt (Sitter, 1962; Pérez-Estaún et al., 1988; Wotte, 2009) (Fig.1A). This is also applicable on a more local scale within the CZ, where only pieces of the pre-Variscan puzzle remain and consequently only a small part of the Devonian succession is exposed (Sitter, 1962; Alonso et al., 2009) (Fig. 2). For instance, the Sabero-Gordón fault zone between the Alba and Pedroso synclines cuts across the pre-Variscan succession, and the anticlinal structure between both synclines is missing (Figs 2, 6; see also Knight et al., 2000). This tectonic shortening emphasises the Devonian facies differences between the successions of this age in both synclines, as the transitional area in between had been tectonically removed.

Relative position of pre-Variscan sections. Sections located within the same tectonic unit approximately retain their relative positions, although the structure itself can be tectonically transported.

All this makes it difficult to establish the size and boundaries of the several Devonian sedimentary domains and pre-Variscan palaeogeographical elements. However, their existence can be proved by given, specific (interpreted) palaeogeographical elements in the pre-Variscan sedimentary successions.

4. Devonian palaeogeography

4.1. The Cantabrian-Iberian trough

Northern Iberian palaeogeography. The Cantabrian-Iberian trough of Lotze (1961) contains the CZ and WALZ, and developed on the northern margin of Gondwana (Aramburu et al., 2002). During the Devonian the Cantabrian-Iberian trough was bordered, on both sides, by rising or stable areas: the Asturian Geanticline (Van Adrichem Boogaert, 1967) and Ebroian Massif (Carls, 1988) on the inner side of the arc, and a formerly existing, unpre-

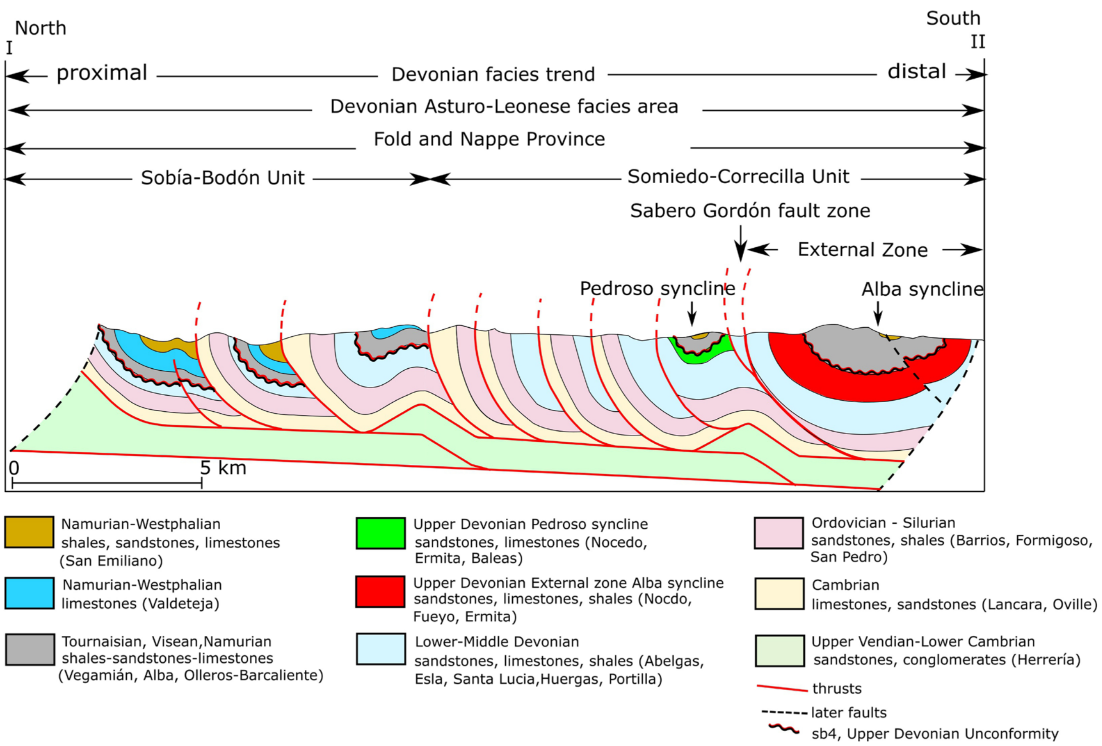

Fig. 2. Thin-skinned imbricated thrust development of the Fold and Nappe Province (modified after Veselovsky, 2004).

served, large source area, which delivered clastics via the Central Iberian Zone from the south-west, postulated by Carls (1988). The CZ Devonian consists mainly of shallow-marine successions, located in a strip between the Asturian Geanticline and Ebroian Massif in the north-east, and the sedimentary trough of the WALZ. The latter unit is a Variscan structural zone that rose from part of the basin located distally, to the west and south of the CZ, and during Early Palaeozoic times was a graben basin (Aramburu et al., 2002), where a rather thick (*c.* 11,000 m) Lower Palaeozoic succession accumulated (Fig. 3). The CZ would present the basin margin of the West Asturian Leonese trough along the north-eastern Cantabro-Ebroian Massif, containing a *c.* 4,500-m-thick Lower Palaeozoic succession of platform and carbonate strata that thin towards the core of the arc (Carls, 1988; Aramburu et al., 2002) (Fig. 4A). The Cantabro-Ebroian Massif emerged several times during phases of the (Late) Devonian, and the repeated uplifts with corresponding unconformities in its interior are preserved along the basin margins, in the shallow-marine strip of the Cantabrian Devonian, e.g., the Upper Devonian sequence boundaries sb1 to 4 of Van Loevezijn (2020) (Fig. 5).

CZ shallow-marine facies area. The Devonian coarse-grained Asturo-Leonese facies succession of Brouwer (1964) consists of sandstones, shales, coarse limestones and microconglomerates, up to 2,000 m thick, characterised by an abundant benthic fauna, with major reef intercalations (Fig. 5), representing shallow-marine, near-coastal environments along the Asturian Geanticline (Van Adrichem Boogaert, 1967). Presently, the area is located mainly in the Fold and Nappe Province (see Fig. 1C), and is bounded by the next tectonostratigraphical unit (Central Asturian Coalfield) towards the core of the arc. Towards the north-east, the Asturo-Leonese succession displays proximal features interrupted by progressively more unconformities of greater importance (Figs 5, 6). In the core area of the CZ, pre-Famennian Devonian strata are absent. The outer boundary of the facies area is formed by the CZ outer limits: the Narcea antiform in the west and the Cenozoic and Mesozoic cover in the south.

CZ pelagic facies area. The Pisuerga-Carrión unit, located in the east of the CZ, consists exclusively of Carboniferous deposits containing

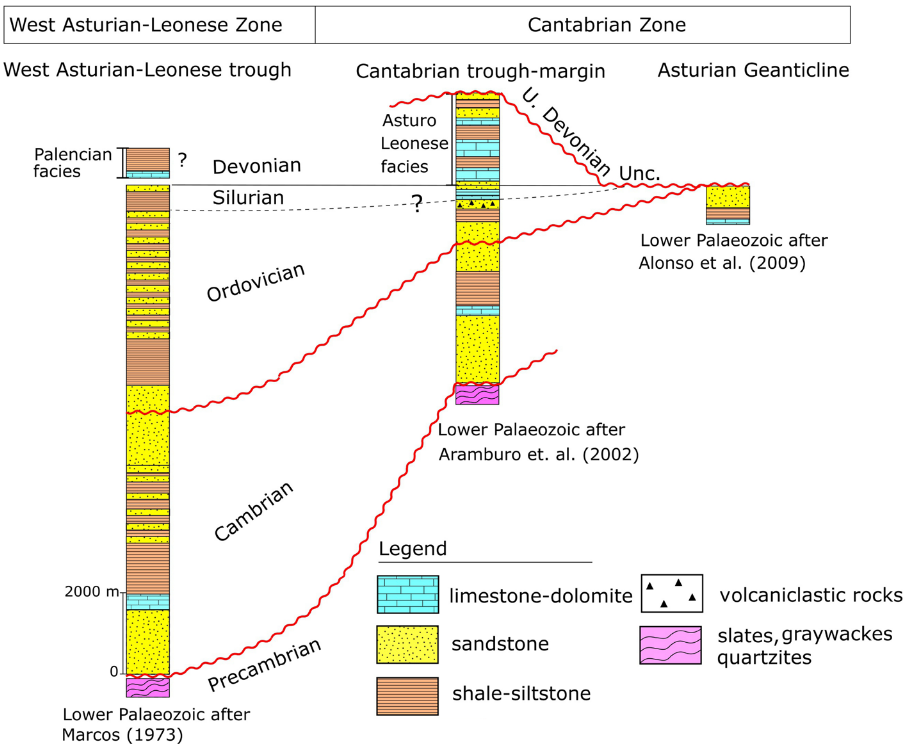

Fig. 3. General thickness and lithology of Cambrian, Ordovician, Silurian and Devonian rocks in the West Asturian-Leonese Zone (WALZ) and Cantabrian Zone (CZ). The WALZ contains the depocentre of the trough. It is assumed that the Devonian condensed calcareous shales of the Palentian facies originally formed in the WALZ (Frankenfeld, 1983, 1984; Marquínez & Marcos, 1984). The CZ represents the trough margin close to the Asturian Geanticline, where a Lower Palaeozoic succession and the Devonian carbonate belts of the Asturo-Leonese facies accumulated.

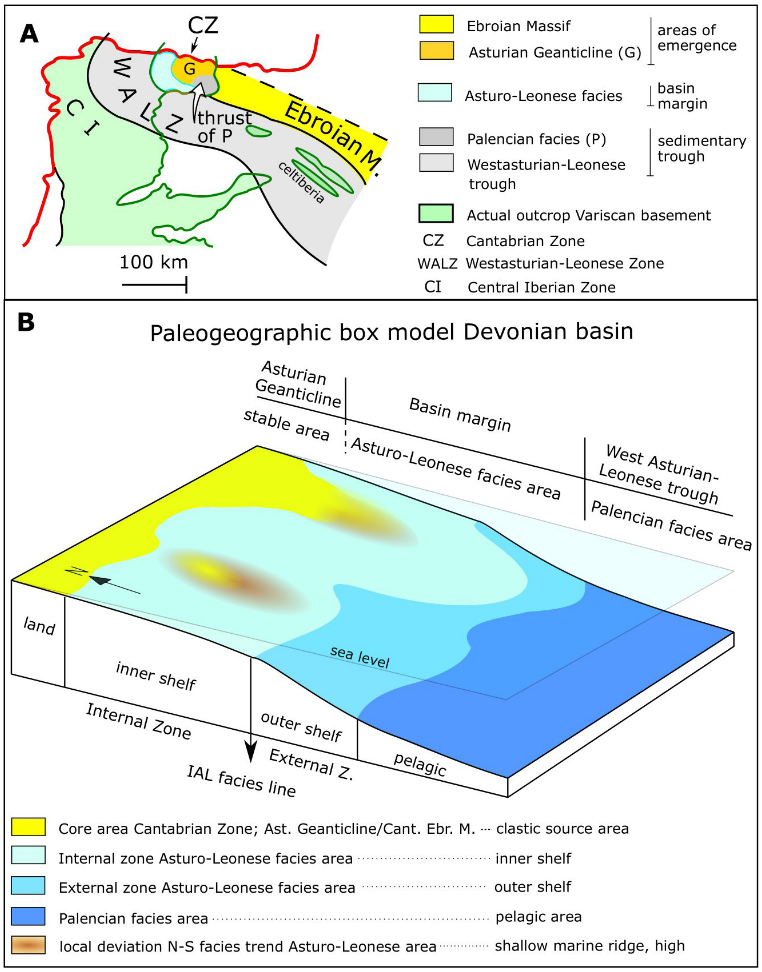

Fig. 4. Devonian facies distribution and box model of the Cantabrian-Iberian trough. **A** – Settings of Devonian facies areas of the CZ within the context of the palaeography of the northern Iberian Massif; palinspastic provenance Palencian facies (P) indicated (modified after Carls, 1988); **B** – Palaeogeographical box model of the Devonian basin.

north-directed thrust sheets made up of Upper Silurian to Lower Carboniferous rocks (Julivert, 1978; Rodríguez-Fernández, 1994) (compare Fig. 1B). The Devonian successions of these nappes are fine grained (Palencian facies of Brouwer, 1964) and are characterised by pelagic deposits and scarce detrital material (Fig. 7). The Lochkovian-Pragian interval of the Palencian facies are shallow-water deposits with small reefal intercalations, comparable to those of the Asturo-Leonese facies. The Pragian-Emsian and younger deposits of the Palentian facies consist of pelagic dark shales with carbonate mudstones, containing scarce benthic fauna. This succession records a low average sedimentation rate and deposition in anoxic or semi-anoxic environments (García-Alcalde et al., 1988). Frankenfeld (1983, 1984) and Henn & Jahnke (1984) demonstrated that the Palencian Devonian was allochthonous, occurring in gravitationally nappes emplaced onto a Carboniferous flysch succession (Ambrose, 1974; Frankenfeld, 1983; Rodríguez-Fernández, 1993). Structural and sedimentological evidence support a provenance for the Palencian facies from the West Asturian-Leonese area, located to the south-west (Frankenfeld, 1983; Rodríguez-Fernández, 1993). The facies is interpreted to represent the southern and western deeper, distal continuation of the shallow-marine Asturo-Leonese facies (Frankenfeld, 1983, 1984; Henn & Jahnke, 1984; Rodríguez-Fernández, 1993; Weil et al., 2013).

4.2. Asturian Geanticline

In the core of the CZ a more stable area existed with a thin Devonian succession; the Cantabrian Block of Radig (1962), Asturian Geanticline of Van Adrichem Boogaert (1967) or Cantabrian Massif of Carls (1988). It is considered the western prolongation of the Ebroian Massif, both forming the Cantabro-Ebroian Massif (Carls, 1983) (Fig. 4A). The Devonian successions are generally thinner, and display more proximal facies towards the core of the CZ, where a few metres of coarse sandstone, conglomerate and coarse limestone of the Famennian–Tournaisian Llombera Beds rest unconformably on Silurian, Ordovician or Cambrian strata (Raven, 1983). This lithostratigraphical unit, defined by

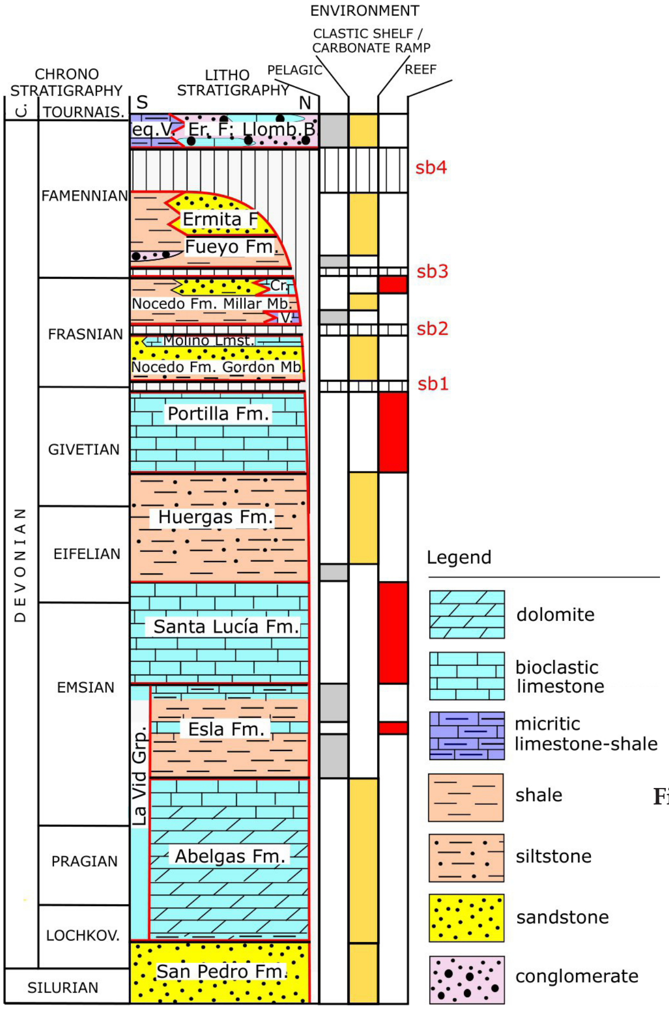

Fig. 5. General Asturo-Leonese lithofacies succession and interpretation of the southern CZ. Cr – Crémenes Limestone, V – Varga Limestone, eq. V – equivalent of the Vidrieros Formation, Er. F. – Ermita Formation, Llomb. B. – Llombera Beds. Devonian units after Reijers (1972), Coo (1974), Suarez de Centi (1988), Keller (1988), Keller et al. (2008) and Van Loevezijn & Van Loevezijn Peña (2017).

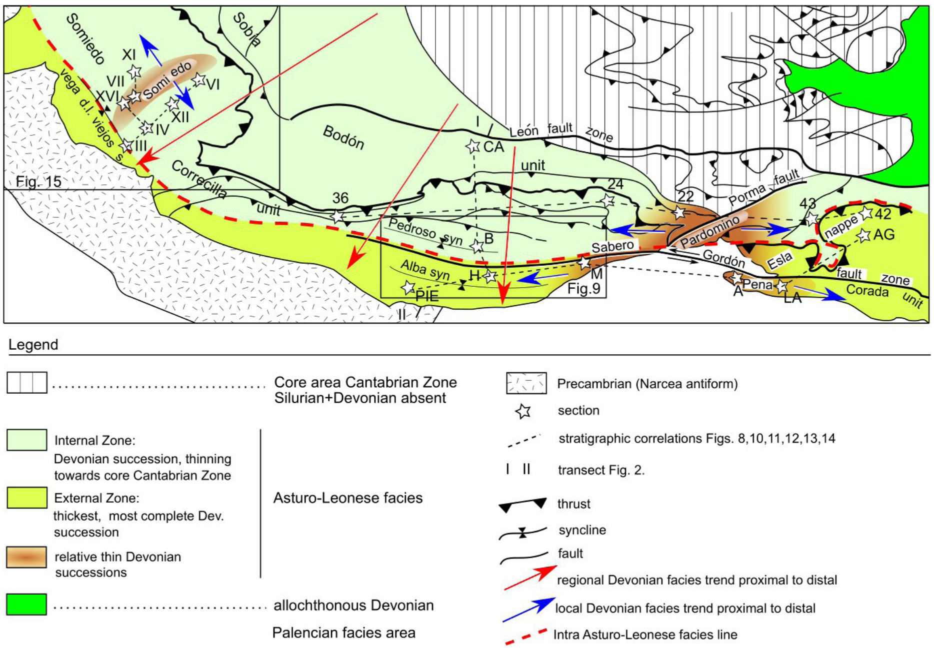

Fig. 6. Facies map of the southern CZ with the Asturo-Leonese facies in the south and west, the Asturian Geanticline in the north and the allochthonous Palencian facies area in the east. Locations of sections and correlations are indicated.

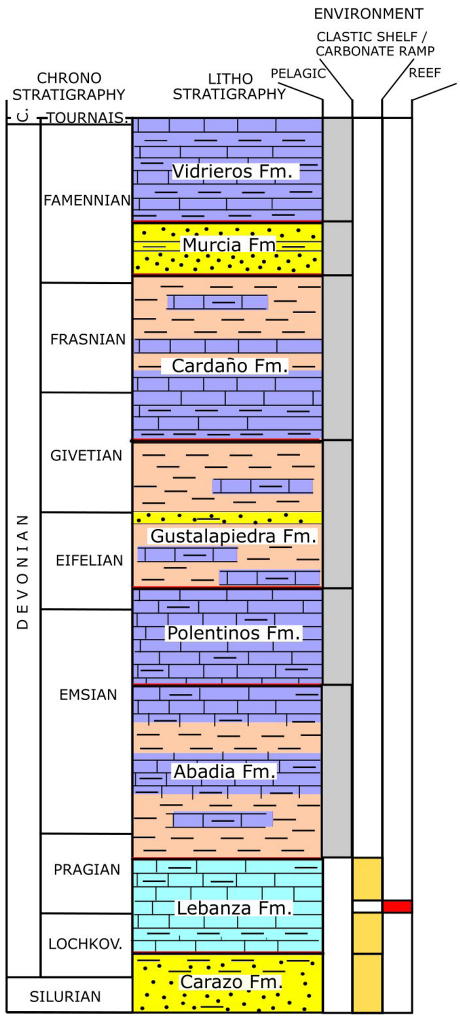

Fig. 7. General Palencian lithofacies succession and interpretation of the southern CZ. For explanations see Figure 5. Devonian units after Van Veen (1966), Henn & Jahnke (1984), García-Alcalde et al. (2000), Sanz-López et al. (2000), García-López et al. (2002) and Fernández-Martínez et al. (2010).

Keller et al. (2008), is equivalent to the unconformable, uppermost part of the Upper Devonian sandstones, classically known as the Ermita Formation.

The Asturian Geanticline did not rise suddenly; the stratigraphical picture makes it clear that the geanticline must already have been a high during the Cambrian (Lotze, 1961); Radig (1962) demonstrated that the Ordovician and Silurian became less complete towards the Asturian Geanticline. However, Aramburu et al. (1992, 2002) noted local outcrops of Middle Ordovician dark shales, indicating a more complex thickness/facies distribution. Subsequent uplift and active erosion of the Asturian Geanticline and the proximal part of the Asturo-Leonese facies area took place during the latest Frasnian and Famennian (Van Loevezijn, 2020), which led to the truncation of the inferred thin Lower Devonian or Silurian successions in the proximal part of the Asturo-Leonese facies area, whilst on the Asturian geanticline itself the Upper Devonian unconformity progressively truncated Lower Palaeozoic rocks (Van Adrichem Boogaert, 1967; Raven, 1983). Palaeocurrent measurements in Upper Devonian successions indicate a sediment transport away from the Asturian Geanticline towards the west and south (Raven, 1983; Van Loevezijn, 1986, 2020), in a similar way to what has been found for the Silurian-Devonian formations (Coo, 1974; Suarez de Centi, 1988; Keller, 1997) (Fig. 6).

4.3. External Zone and Intra Asturo-Leonese facies line

The External Zone of the Asturo-Leonese facies area is an approximately 5-km-wide facies belt, which, contrasting to the inner zone with its thin incomplete Upper Devonian succession, comprises a thick Frasnian to lower Famennian interval (Figs 1C, 6). The External Zone developed during the Frasnian as a consequence of the rise of the nearby core area of the CZ (Sjerp, 1967; Van Loevezijn, 2020), and lasted into the Famennian. It represents a depositional Late Devonian area of subsidence, where clastics were deposited from the nearby area of the Asturian Geanticline and the proximal parts of the Asturo-Leonese facies area. The Intra Asturo-Leonese facies line acted as a Late Devonian hinge line between the area of uplift and erosion in the core of the CZ and the External Zone of subsidence and sedimentation in the outermost rim of the zone (Raven, 1983; Van Loevezijn, 1986). The Upper Devonian succession in the External Zone is organised into three wedges, each with a coarsening- and shallowing-upward trend and with a basal unconformity, that evolves into stratigraphical continuity away from the Asturian Geanticline to the distal part of the External Zone. They are the sequences A, B and C of Van Loevezijn & Van Loevezijn Peña (2017) (Fig. 8).

The wedge of the Millar Member of the Nocedo Formation (sequence B) and the wedge of the Fueyo-Ermita formations (sequence C) occur only in the External Zone, and are dominated by storm-bedded shale-sandstone deposits, with cross-bedded sandstones and carbonates in the top. Not only did subsidence of the External Zone create accommodation space for a thick Frasnian-Famennian succession, the subsidence coupled with the nearby enlargement of the uplifted northern area also led to steep, unstable depositional slopes, as

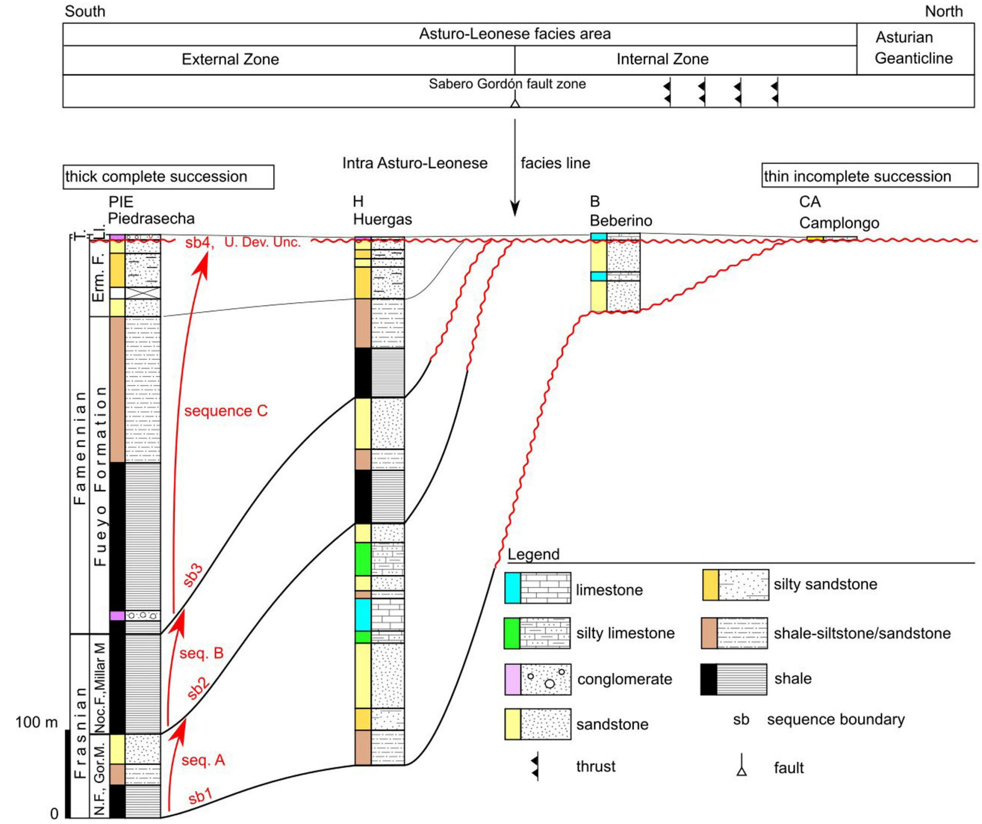

Fig. 8. Upper Devonian stratigraphical north-south transect of the Asturo-Leonese facies area, perpendicular to depositional strike, demonstrating the depositional prism, stratal thinning and erosion events towards the northern massif of the Asturian Geanticline. For location of sections see Figure 6. Upper Devonian after Van Loevezijn & Van Loevezijn Peña (2017).

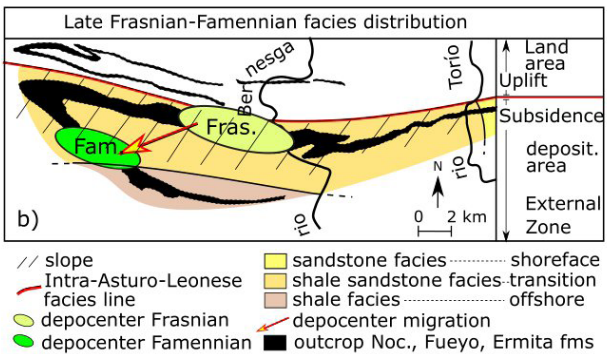

Fig. 9. Upper Devonian facies distribution and interpretation of the southern Cantabrian Mountains, with the Frasnian-Famennian depositional shift (modified after Van Loevezijn, 2022).

revealed by the slumped deposits that crop out in sections such as Matallana, Llombera, Sorribos de Alba, Piedrasecha and Puente de las Palomas (Van Loevezijn, 2022), as well as a Frasnian-Famennian depositional shift away from the uplifted area, towards the outermost part of the External Zone (Van Loevezijn & Raven, 2017, their fig. 14; Van Loevezijn, 2020, his fig. 18) (Fig. 9). The overall characteristics of the zone are: 1) its location on the outermost edge of the CZ, and 2) its thick (Upper) Devonian development, which differs from the inner part of the CZ.

4.4. Pardomino High

The distribution of the Devonian sedimentary successions within the Asturo-Leonese facies area indicates that the boundary between the source (Asturian Geanticline) and shelf (Asturo-Leonese facies area) areas was not a linear feature, but that it had embayments and headlands, defined by ridges and highs, which exerted a major control on the sedimentary patterns and affected facies belts (Fig. 6). During the Early Devonian, carbonates spread rapidly across the partly exposed siliciclastic land area ('San Pedro Land' of Keller, 1997), onlapping the Asturian Geanticline in the north. The abrupt shift to deeper facies represents the transgressive surface between the sandstones of the underlying San Pedro Formation and the transitional unit of the overlying Abelgas Formation (La Vid Group). The

Abelgas successions in the eastern part of the Luna-Bernesga area, and in the western part of the Esla area show a thinning of strata with erosion events (Fig. 10). The sections lie in different thrusts, and their mutual distance has not been measured, nor have their different tectonic locations been accounted for, which makes the spatial palaeogeographical interpretation difficult. However, although the interpretation compares successions from different thrust units, the area with thin successions was interpreted as a positive palaeogeographical feature, the so-called Pardomino High, by Evers (1967) and Keller (1988, 1997). The palaeogeographical feature curved the straight-forward, north-south proximal-distal trend of the Devonian Cantabrian Basin. A similar palaeogeographical picture can be obtained from the Frasnian east-west transect, with thick, continuous sections in the outermost areas, and a thinning, coarsening and shallowing trend towards the inner central part of the Bernesga-Esla area (Fig. 11). However, between Matallana and San Adreán the transect crosses the Porma fault, which again poses some uncertainties. Thus, we see a systematic Devonian stratal thinning in the Esla nappe from east to west into the Pardomino area, and a stratal thinning in the Correcilla unit from west to east towards the Pardomino area, separated by the Porma fault, which is a Variscan tear fault (Weil et al., 2010), running perpendicular to the strike of the thrust faults (Weil et al., 2013) and, as a consequence, a tectonic juxtaposition occurs of different parts of the Devonian basin between both sides of the fault. The displacement along the Porma fault (Fig. 6), the north-south tectonic shortening by the thrusts and the left-lateral displacement along the Sabero-Gordón fault Zone, make the pre-Variscan connection between Bernesga and Esla areas difficult, and complicates the stratigraphical relation between the Bernasga and Esla areas. Palaeomagnetic data document for the Esla unit a secondary rotation of the initial thrusting and folding of 90° counterclockwise (Weil, 2006; Wotte, 2009; Weil et al., 2013). Therefore, a primary position of this unit in a more south-westerly location, close to the Correcilla unit must be assumed (Keller et al., 2007; Wotte, 2009). This is in accordance with the Upper Devonian sediment successions of the Alba syncline of the Correcilla unit and the Peña Corada structure of the Esla unit; both are part of the External Zone of the Asturo-Leonese facies area (Raven, 1983; Van Loevezijn, 1986).

In contrast, the Famennian transect shows a slight coarsening and thinning of the succession/stratigraphical units towards the east from the Bernesga area into the Esla area, where the transgressive base onlaps sequence boundary 1 (Fig. 12). This early Famennian transgression is recorded in dark shales in the basal part of the Fueyo Formation, which constitutes the transgressive system tract of Upper Devonian sequence C (Van Loevezijn

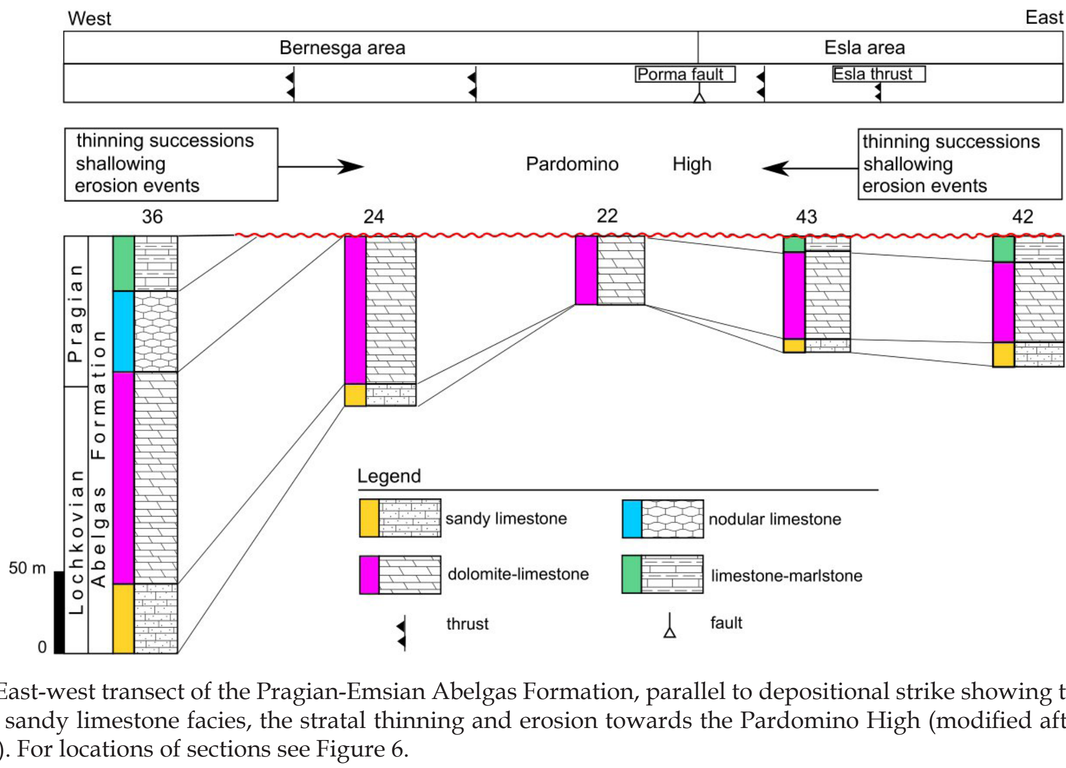

Fig. 10. East-west transect of the Pragian-Emsian Abelgas Formation, parallel to depositional strike showing the onlapping sandy limestone facies, the stratal thinning and erosion towards the Pardomino High (modified after Keller, 1997). For locations of sections see Figure 6.

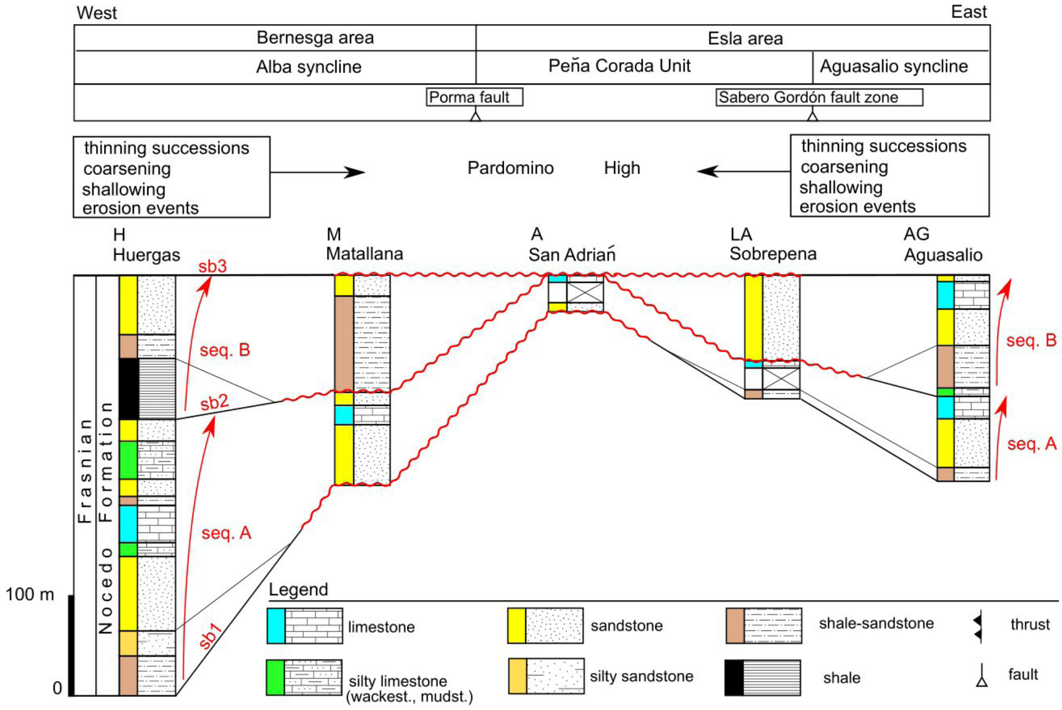

Fig. 11. Frasnian stratigraphical east-west transect demonstrating a trend of coarsening and stratal thinning towards the Pardomino High. For location of sections see Figure 6.

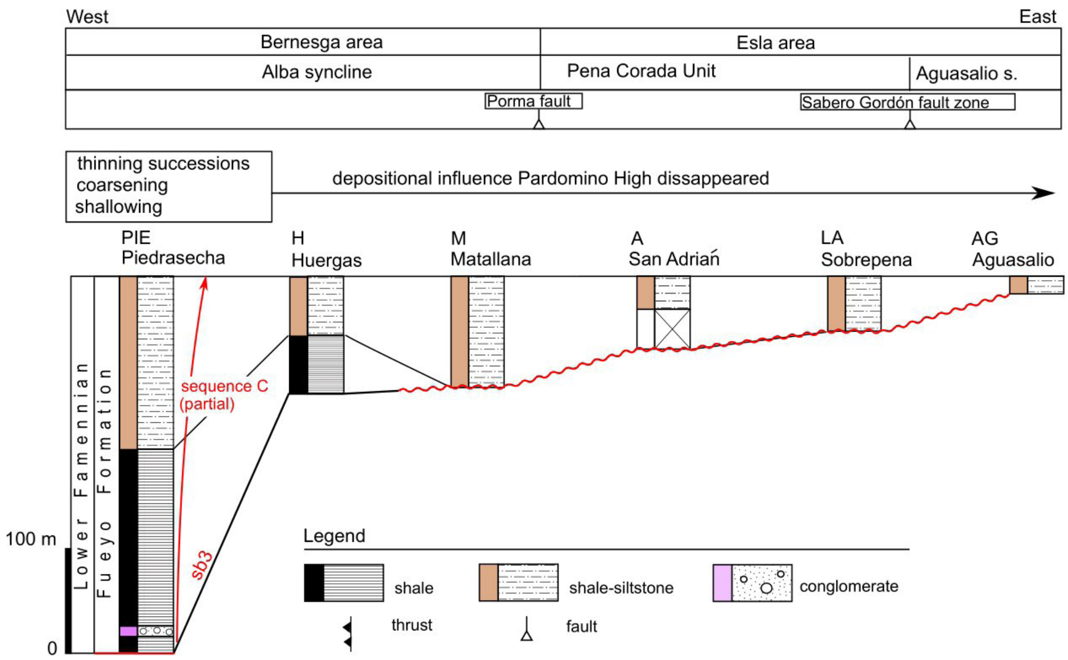

Fig. 12. Early Famennian east-west transect, showing stratal thinning and onlap stratigraphical relation towards the east. For location of sections see Figure 6.

& Van Loevezijn Peña, 2017). It seems obvious that the influence of the Pardomino High on the Famennian sediment pattern had disappeared. Thus, the Pardomino High was a Devonian positive palaeogeographical feature, with a strong depositional influence that controlled the Devonian depositional patterns up to the Early Famennian.

From the above it becomes clear that a simple linear facies trend between clastic source area in the north (Asturian Geanticline) and the sedimentation basin in the south is an oversimplification of the likely palaeogeography, and that local palaeogeographical features had a great impact on Devonian sedimentation.

4.5. Somiedo High

The Portilla Formation of the Somiedo area is subdivided into a lower and upper biostromal limestone with biohermal intercalations (members A and C) and a more siliciclastic middle unit (Member B) (Ten Have, 1979; Raven, 1983). This formation, like all Devonian formations of the Asturo-Leonese facies area, thins out towards the core of the CZ (Fig. 13). However, a narrow zone of thinly developed Portilla overprints this general palaeogeographical trend. This was named the Somiedo High by Raven (1983); it occurs in the stratigraphical pattern of the Portilla. Thinning across sections of the Somiedo High reaches up to 50 per cent (Fig. 14, sections VII and XVI).

From Lower-Middle Devonian limestones of the Santa Lucía Formation there are indications that the Somiedo High may already have existed during the Emsian–Eifelian, when in the Somiedo area a south-west to north-east running belt between the Vega de las Viejos and the Saliencia synclines existed of thin Santa Lucía Formation, containing a high grain-mud ratio (as based on internal reports of the Department of Palaeontology and Stratigraphy, University of Leiden, the Netherlands), and thicker successions towards the south-east. However, the data set is not very detailed, and conclusions must be treated with caution. Successions of the overlying Upper Devonian Nocedo and Ermita formations in the Somiedo area do not indicate a local north-east to south-west thin depositional zone, but a general Devonian thinning from the External Zone towards the core of Asturian Geanticline (Van Loevezijn, 1986; Van Loevezijn & Raven, 2021).

5. Discussion

The existence of all the Devonian palaeogeographical features of the CZ area are recorded in the stratigraphical correlation patterns, and all the pre-Variscan palaeogeographical features suffer from Variscan disruption, affecting the reliability of palaeogeographical elements interpreted. Therefore, some of these pre-Variscan features must be discussed briefly.

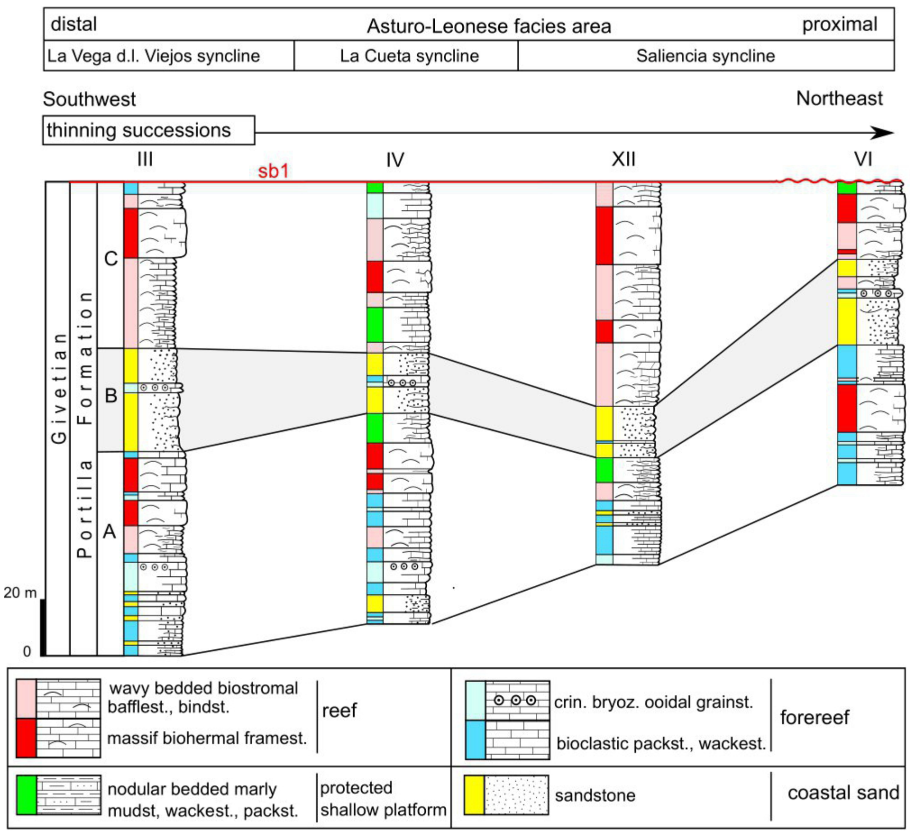

Fig. 13. South-west to north-east transect of the Givetian Portilla Formation of the Somiedo area, with stratal thinning towards the core of the CZ (after Ten Have, 1979). For location of sections see Figure 6.

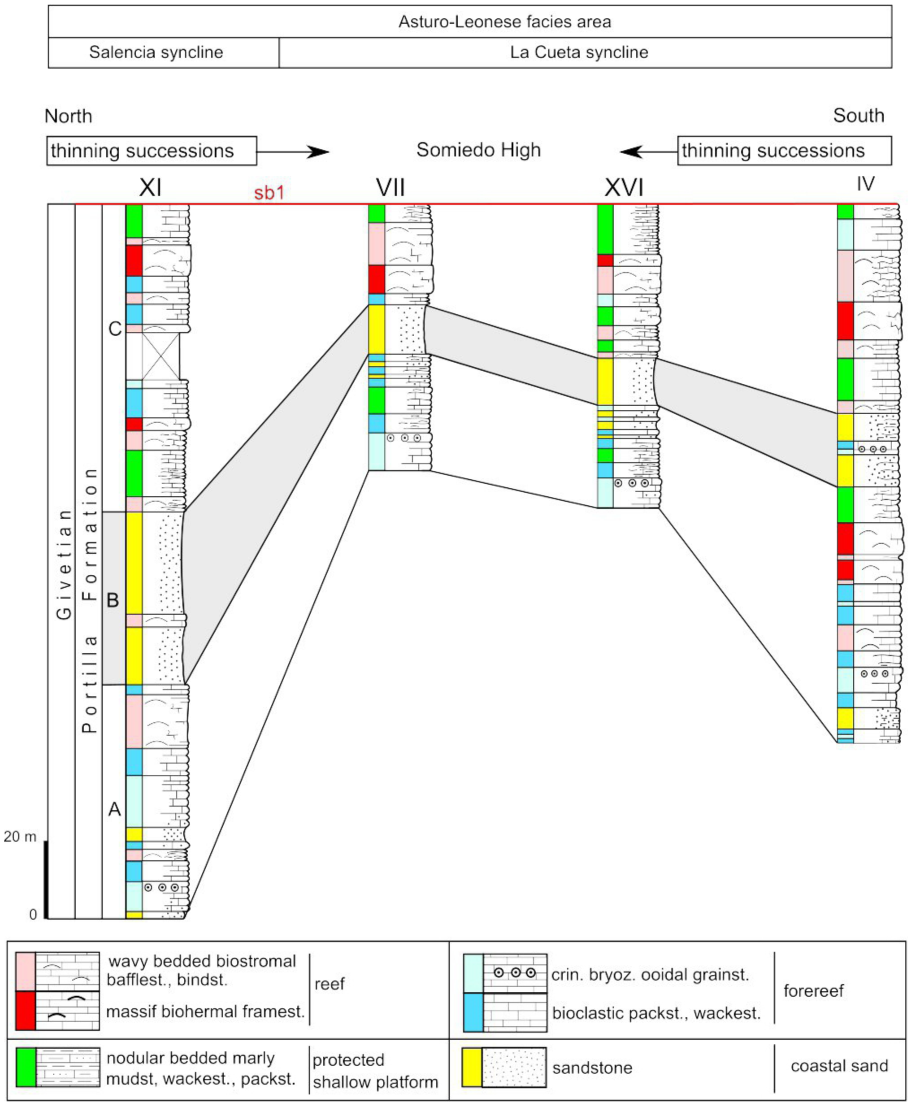

Fig. 14. North-south transect of the Givetian Portilla Formation of the Somiedo area, where a thinly developed Portilla indicates the location of the Somiedo High (after Ten Have, 1979). For location of sections see Figure 6.

The Pardomino High. This feature is recorded in Lower-Upper Devonian facies transects of the eastern Bernesga area and western Esla area. However, the exact location of its boundary is complicated by Variscan tectonic features; the north-south tectonic shortening by the thrusts, the left-lateral displacement along the Sabero-Gordón fault Zone and the displacement along the Porma fault (Fig. 6). Therefore, only an indication can be given of the location and shape of the Pardomino High. However, although the structure of the Alba syncline and the Peña-Corada unit are both bounded by Variscan faults, strata are not that much deformed, and in both structures the sections have more or less preserved their relative positions. Both tectonic units contain a Devonian shallowing and stratal thinning trend; the Alba syncline towards the east and the Peña-Corada unit towards the west.

The Somiedo High. This high is characterised by a narrow zone of thinly developed Portilla. However, based on the 1:50,000 map Hoja 76-Pola de Somiedo (Rodríguez-Fernández, 1979), the Portilla Formation in the northern limb of the La Cueta syncline is faulted and thrusted, and therefore stratigraphical conclusions should be view critically. However, even these thin sections from the north-western part of the syncline contain a complete threefold subdivision of the Portilla, and also the sections of the Vega de losViejos syncline, the Saliencia syncline and the La Cueta syncline close to the northern limb, display thin successions of the formation (sections VIII, XII and XV), indicating that thinning is probably a primary, depositional feature (Fig. 15). The sections are all located within the same thrust structure of the Somiedo-Cor-

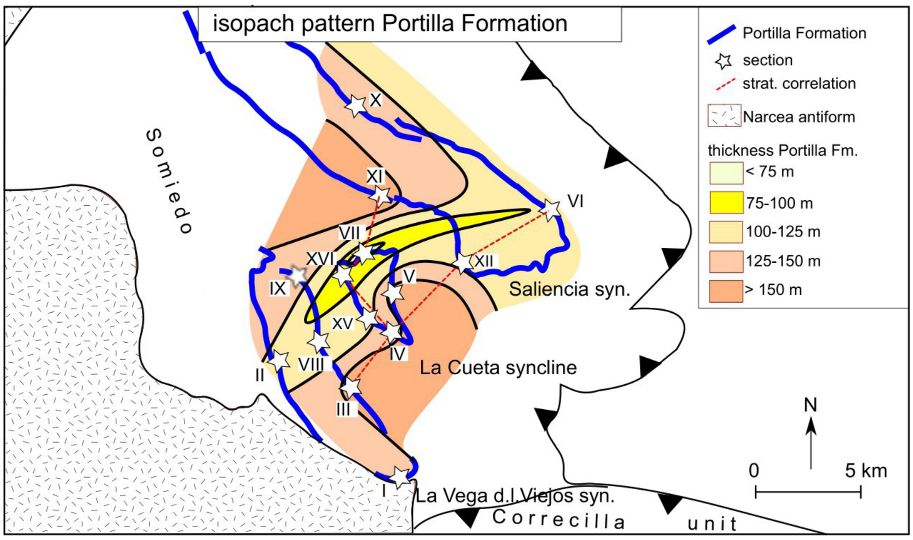

Fig. 15. Isopach map of the Givetian Portilla Formation in the Somiedo area, showing a thinly developed succession, where subsidence was lower (after Ten Have, 1979). For location of sections see Figure 6.

recilla unit. Thus, they approximately retain their relative positions, although the structure itself may have been tectonically transported. The dimension and shape of the palaeogeographical feature suffered mainly from shortening by the folds of the syncline structures and by bending of the orocline, but probably hardly by large thrust displacements. There are indications that the palaeogeographical feature already existed during the Emsian-Eifelian. However, these are not very convincing and more research is needed.

The Intra Asturo-Leonese facies line and the External Zone. The Intra Asturo-Leonese facies line along the outer margin of the CZ separates an outer area with a thick Upper Devonian succession, the External Zone, from the inner part with a thin incomplete Upper Devonian. However, the Intra Asturo-Leonese facies line in part coincides with the Esla thrust front in the east, whereas to the west it coincides with the Sabero-Gordón fault zone, located between the Alba and Pedroso synclines, and continues to the Sil area where it runs across the Vega de los Viejos syncline (Fig. 6). Fernández et al. (2021) demonstrated that facies changes between both limbs of the Vega de los Viejos Syncline seem to occur in a gradual way. However, these gradual facies changes occur in the transgressive Famennian–Tournaisian Llombera Beds (Ermita Formation) above the upper Devonian Unconformity, the fundamental change to Carboniferous sedimentation patterns (Keller et al., 2008). The underlying shales of the Fueyo Formation and sandstones of the Ermita Formation of sequence C are absent in the north-eastern limb of the syncline (Van Loevezijn & Raven, 2021), and the Intra Asturo-Leonese facies line is located between both limbs. Thus, the character of the boundary varies along the External Zone, and locally coincides with Variscan and later faults and thrust fronts. However, everywhere the boundary line separates the area of thick Upper Devonian development from the inner area of thin, incomplete successions. Therefore, it is a pre-Variscan palaeogeographical feature, with a significant Devonian facies change across its bounding line. In fact, the line connects the Upper Devonian facies and thickness changes in the different tectonic units, and the facies trend is emphasised by Variscan faulting, folding and thrust movements, locally bringing rocks together which were originally further apart. Thus, although the facies line is a sharp boundary, probably also transitional facies belts once existed between the External- and inner facies domains.

5.1. Reliability of palaeogeographical interpretations

The approximate location of the pre-Variscan palaeogeography is pinpointed by the Devonian sections and the stratigraphical correlation transects. However, for the original pre-Variscan palaeogeographical shape, we must bear in mind Variscan tectonic features: the complex shift of the thrust units (Alonso et al., 2009), the tectonic shortening of up to 70 per cent (Pérez-Estaún et al., 1988) and, finally, the bending of the orocline (Weil, 2006; Weil et al., 2013). Tectonic thrust-shifts are directed towards the core of the CZ, that is, in the investigated southern area they have approximately a north(easterly) directed shift (Fig. 1B). The east-west correlations are approximately perpendicular (and oblique) to the north-eastern thrust displacement, and therefore suffered less from extreme shortening (Fig. 6). Moreover, facies trends within a single Variscan structure, that is, the Alba syncline, Peña Corada unit, Vega de losViejos-, La Cueta- and Saliencia synclines, contain less Variscan cross cutting and tectonic deformation. Within each structure or thrust, sections approximately retain their relative positions, although the structure itself was tectonically transported. The relative movements along the vertical fault planes of strike-slip faults can make interpretations of the spatial relation between successions on both sites of the fault difficult. For example, the Porma fault runs approximately parallel to the north-eastern thrust transport direction, crossing the pre-Variscan Pardomio High and separating the Esla area from its western Palaeozoic region, and the Sabero-Gordón fault zone contains a left-lateral strike-slip displacement of about 15–20 km (Bastida et al., 1976; Alonso et al., 2009) and also crosses the Pardomino High, disrupting the shape of the Devonian feature. In addition, the Intra-Asturo-Leonesefacies line partly coincides with the Esla thrust front, whereas to the west it is located between the Alba and Pedroso synclines, whose bounding fault also implies significant shortening (Fig. 2).

6. Conclusions

In Figure 16, pre-Variscan palaeogeographical features are lined up, based on the stratigraphical information recorded in the Devonian successions. The Cantabrian-Iberian trough, and the area of uplift and emergence of the Asturian Geanticline in the core of the CZ, cover the entire Devonian.

The Pardomino High with a thin Devonian succession which existed until the Famennian, when it was drowned by the early Famennian transgression, recorded in dark shales in the basal part of the Fueyo Formation. The Somiedo High is recorded in a local thin development of the Givetian Portilla Formation in the Somiedo area. These Portilla reef deposits vary significantly in thickness and facies over short distances, and their deposition and lateral facies distribution was mainly tectonically con-

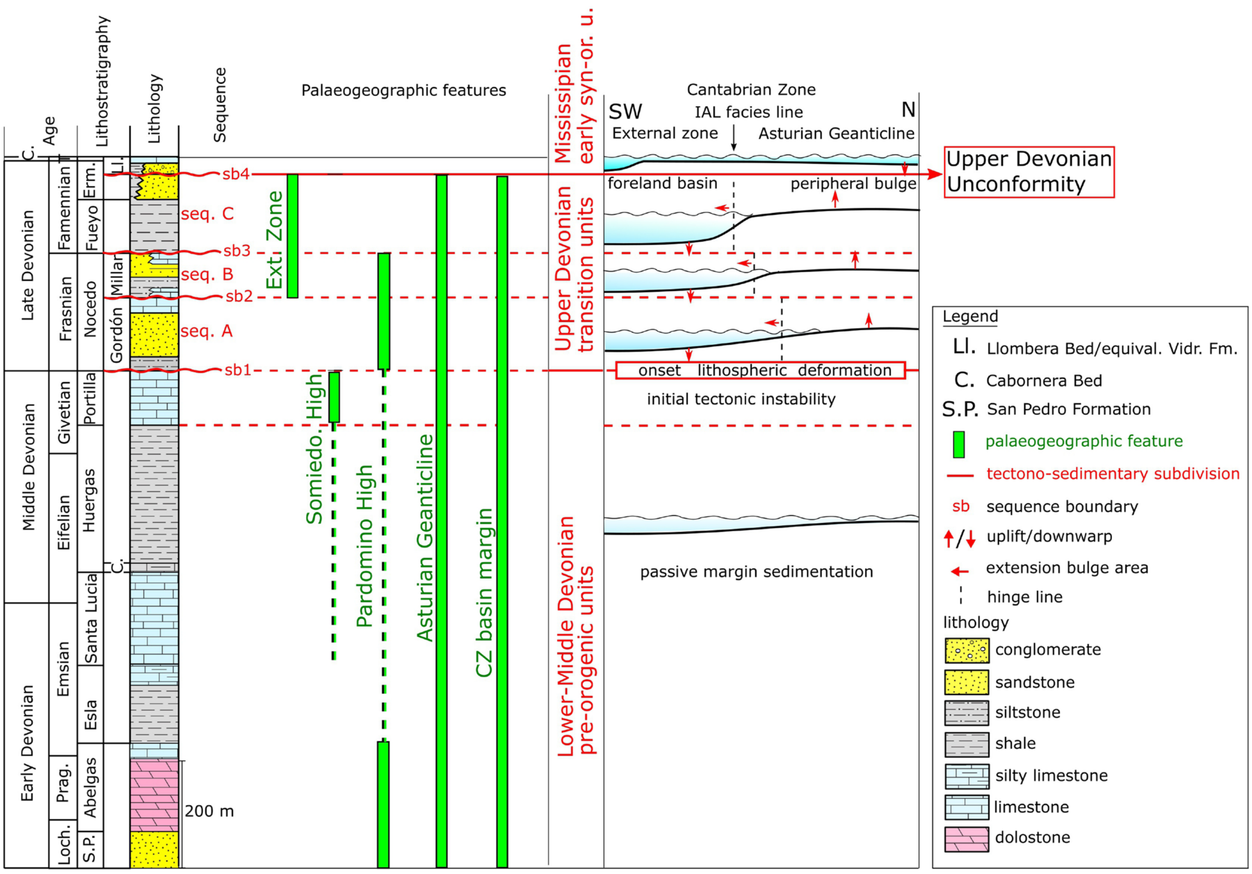

Fig. 16. Devonian stratigraphy of the Asturo-Leonese facies in the southern Cantabrian Mountains, showing the palaeogeographical features and the tectono-sedimentary development.

trolled, indicating tectonic instability. The Somiedo High can be the expression of such a tectonically controlled palaeogeographical feature. However, there are indications that the high already existed during Early Devonian times.

The External zone contains the most distal and thickest Upper Devonian facies succession of the CZ. The Intra-Asturo-Leonese facies line represents the bounding line between the External Zone and the inner part of the CZ with erosion events and thin proximal facies successions. The zone developed during the Late Devonian, when northern Iberia became part of the collision between the Gondwana and Laurussia continents. The External Zone can be interpreted as a distal foreland basin with the Intra-Asturo-Leonese facies line as the hinge between the area of rapid subsidence in the south and west, and the uplifted peripheral bulge of the inner part of the Asturo-Leonese facies area and the Asturian Geanticline in the north.

Finally, the Upper Devonian Unconformity is the result of the Frasnian-early Famennian uplift and erosion of the core of the CZ, and marks the end of the depositional influence of all pre-Variscan palaeogeographical features. In fact, the unconformity is the start of the fundamental reorganisation of the depositional system to Carboniferous settings. Probably all the pre-Variscan palaeogeographica features suffered from Variscan disruption. Therefore, the exact location and shape of these old pre-Variscan structures may be controversial, and only an approximation of their estimated relative palaeogeographical position can be given.

Acknowledgements

Thanks are due to J.G.M. Raven (Naturalis Biodiversity, Leiden) for assistance during the writing of an early version of the manuscript, as well as to A.H.M. ten Have and J.C. Deelman for data on the Portilla and Santa Lucía formations (unpublished reports, former Department of Palaeontology and Stratigraphy, University of Leiden). Constructive reviews by two anonymous reviewers have considerably improved the present paper.

References

Abati, J., Gerdes, A., Fernández-Suárez, J., Arenas, R., Whitehouse, M.J. & Díez Fernández, R., 2010. Magmatism and early-Variscan continental subduction in the northern Gondwana margin recorded in zircons from the basal units of Galicia, NW Spain. *Geological Society of America Bulletin* 122, 219–235.

Alonso, J.L., 1987. Sequences of thrust and displacement transfer in the superpost duplexes of the Esla Nappe region (Cantabrian Zone, NW Spain). *Journal of Structural Geology* 9, 969–983.

Alonso, J.L., Marcos, A. & Pulgar, J.A., 1991. Persistent basement wrenching as controlling mechanism of Variscan thin-skinned thrusting and sedimentation, Cantabrian Mountains Spain; Comment. *Tectonophysics* 194, 171–182.

Alonso, J.L., Marcos, A. & Suárez, A., 2009. Paleogeographic inversion resulting from large out of sequence breaching thrusts: the León Fault (Cantabrian Zone, NW Spain. A new picture of the external Variscan Thrust Belt in the Ibero-Armorican Arc. *Geologica Acta* 7, 451–473.

Alonso, J.L., Marcos, A., Villa, E., Suárez, A., Merino-Tomé, O. & Fernández, L.P., 2015. Mélanges and other types of block-in-matrix formations in the Cantabrian Zone (Variscan Orogen, northwest Spain): origin and significance. *International Geology Review* 57, 563–580.

Alonso, J.L., Pulgar, J.A., García-Ramos, J.C. & Barba, P. 1996. Tertiary basins and Alpine tectonics in the Cantabrian Mountains (NW Spain). [In:] Friend, P.F. & Dabrio C.J. (Eds): *Tertiary basins of Spain: Tectonics, Climate and Sea-Level Changes.* Cambridge University Press, Cambridge 214–227.

Ambrose, T., 1974. The lower Palaeozoic rocks of northern Palencia. *Breviora Geologica Astúrica* 18, 49–53.

Aramburu, C., Méndez Bedia, I. & Arbizu, M., 2002. The Lower Palaeozoic in the Cantabrian Zone (Cantabrian Mountains, NW Spain). *Cuadernos de Museo Geominero* 1, 35–49.

Aramburu, C., Truyols, J., Arbizu, M., Méndez-Bedia, I., Zamarreño I., García-Ramos, J.C., Suarez de Centi, C. & Valenzuela, M., 1992. El Paleozoico Inferior de la Zona Cantábrica [The Lower Paleozoic of the Cantabrian Zone]. [In:] J.C. Gutiérrez Marco, J. Saavedra & I. Rábano (Eds): *Paleozoico Inferior de Ibero-América* [*Lower Paleozoic of Ibero-America*]. Universidad de Extremadura, Badajoz, 397–421 (in Spanish).

Bastida, F., Marcos, A, Arboleya, M.L. & Méndez, I., 1976. La unidad Peña Corada y su relación con el Manto de Esla (Zona Cantábrica, NW de Espana) [The Peña Corada unit and its relationship with the Manto de Esla (Cantabrian Zone, NW Spain)]. *Breviora Geologíca Asturica* 4, 49–55 (in Spanish).

Brouwer, A., 1964. Deux facies dans le Dévonien des Montagnes Cantabriques Méridionales [Two facies in the Devonian of the Southern Cantabrian Mountains]. *Brevoria Geologica Asturica* 4, 3–10 (in French).

Carls, 1983. La Zona Asturooccidental-Leonesa en Áragon y el macizo del Ebro como prologación del Macizo Cantábrico. Libro jubilar J.M. Ríos [The Asturoccidental-Leonesa Zone in Áragon and the Ebro massif as an extension of the Cantabrian Massif. Jubilee book J.M. Ríos]. *Memorias del Instituto Geológico y Minero de Espana* III, 11–32 (in Spanish).

Carls, 1988. The Devonian of Celtiberia (Spain) and Devonian Paleogeography of SW Europe. [In:] N.J. McMillan, A.F. Embry & D.J. Glass (Eds): *Devonian of the World.* Canadian Society of Petroleum Geologists, Calgary, Memoire 14, 421–466.

Colmenero, J.R., Fernández, L.P., Moreno, C., Bahamonde, J.R., Barba, P., Heredia, N. & González, F., 2002. Carboniferous. [In:] W. Gibbons & T. Moreno (Eds): *The Geology of Spain*. The Geological Society, London, 93-116.

Colmenero, J.R., Suarez-Ruiz, I., Fernandez-Suarez, J., Barba, P. & Llorens, T., 2008. Genesis and rank distribution of Upper Carboniferous coal basins in the Cantabrian Mountains, Northern Spain. *International Journal of Coal Geology* 76, 187–204.

Coo, J.C.M., 1974. *Lithostratigraphy of the Devonian Santa Lucía Limestones in Leon, Spain*. University of Leiden, 87 pp.

Díez Fernández, R., Arenas, R., Pereira, M.F., Sánchez Martínez, S., Albert, R., Martín Parra, L.M., Rubio Pascual, F.J. & Matas, J., 2016. Tectonic evolution of Variscan Iberia: Gondwana-Laurussia collision revisited. *Earth-Science Reviews* 162, 269–292.

Espina, R.G., Alonso, J.L. & Pulgar, J.A., 1996. Growth and propagation of buckle folds determined from syntectonic sediments (the Ubierna fold belt, Cantabrian Mountains, N Spain). *Journal of Structural Geology* 18, 431–441.

Evers, H.J., 1967. Geology of the Leonides between the rivers Bernesga and Porma (Cantabrian Mountains, NW Spain). *Leidese Geologische Meded*elingen 41, 83–151.

Fernández, L.P., García-Alcalde, J.L. & Alonso, J.L., 2021. La Formación Ermita en el sinclinal de Vega de los Viejos [The Ermita Formation in the Vega de los Viejos syncline]. *Geotemas* 18, 150–153 (in Spanish, with English summary).

Fernández, L.P., Nose, M., Fernández Martinez, E., Mendez Bedía, I., Schröder, S. & Soto, F., 2006. Reefal and mud mound facies development in the Lower Devonian La Vid Group at the Colle outcrops (León province, Cantabrian Zone, NW Spain). *Facies* 52, 207–327.

Fernández-Martínez, E, Fernández, L.P., Méndez-Bedia, I., Soto, F. & Mistian, B., 2010. Earliest Pragian (Early Devonian) corals and stromatoporoids from reefal settings in the Cantabrian Zone (N Spain). *Geologica Acta* 8, 301-323.

Fillon, C., Pedreira, D., van der Beek, P.A., Huismans, R.S., Barbero, L. & Pulgar, J.A., 2016. Alpine exhumation of the central Cantabrian Mountains, Northwest Spain. *Tectonics*, 35, 339–356.

Frankenfeld, H., 1983. El manto de Monto-Arauz: interpretación estructural de la región del Pisuerga-Carrión (Zona Cantábrica, NW de España) [The Monto-Arauz mantle: structural interpretation of the Pisuerga-Carrión region (Cantabrian Zone, NW Spain)]. *Trabajos De Geología* 13, 37–49 (in Spanish, with English summary).

Frankenfeld, H., 1984. Deckenbewegungen im Namur der östlichen Kantabrischen Gebirges und die damit verbundenen Vorstellungen über die Paläogeographie der Namur- und prä- Namur-Schichen [Nappe movements in the Namur of the eastern Cantabrian Mountains and the associated ideas about the paleogeography of the Namur and pre-Namur strata]. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* 135, 223–241 (in German, with English summary).

Gallastegui, J., Javier, A. Pulgar, J.A. & Gallart, J., 2016. Alpine tectonic wedging and crustal delamination in the Cantabrian Mountains (NW Spain). *Solid Earth* 7, 1043–1057.

García-Alcalde, J.L., Montesinos, J.R., Truyols-Massoni, M., García-Lopez, S., Arbizu, M.A. & Soto, F., 1988. El Silúrico y el Devónico del dominio Palentino (NO de España) [The Silurian and Devonian of the Palentino domain (NW of Spain)]. *Revista Sociedad Geologico Espaa* 1, 7–13 (in Spanish, with English summary).

García-Alcalde, J.L, Truyol-Massoni, M., Pardo-Alonso, M., Bultynck, P. & Carls, P., 2000. Devonian chronostratigraphy. *Courier Forschungsinstitut Senckenberg* 225, 131–144.

García-López, S., Jahnk, H. & Sanz-López, J., 2002. Uppermost Pridoli to Upper Emsian stratigraphy of the Alto Carrión Unit, Palentine Domain (Northwest Spain). [In:] S. García-López & F. Bastida (Eds): *Palaeozoic conodonts from northern Spain. Eight International Conodont Symposium held in Europe*. Publicaciones del Instituto Geológico y Minero de España (Serie: Cuadernos del Museo Geominero 1, 229–257.

Gutiérrez-Alonso, G., 1996. Strain partitioning in the footwall of the Somiedo Nappe; structural evolution of the Narcea Tectonic window, NW Spain. *Journal of Structural Geology* 18, 1217–1229.

Gutiérrez-Alonso, G., Fernández-Suárez, J., Pastor-Galán, D., Johnston, S.T., Linnemann, U., Hofmann, M., Shaw, J., Colmenero, J.R. & Hernández, P., 2015. Significance of detrital zircons in Siluro-Devonian rocks from Iberia. *Journal of the Geological Society* 172, 309–322.

Henn, A. & Jahnke, H., 1984. Die palentinische faziesentwicklung im Devon des Kantabrischen Gebirges [The Palentine facies development in the Devonian of the Cantabrian Mountains]. *Zeitschrif der Deutschen Geologischen Gesellschaft* 135, 131–147 (in German, with English summary).

Hofmann, M.H. & Keller, M., 2006. Sequence stratigraphy and carbonate platform organisation of the Devonian Santa Lucia Formation, Cantabrian Mountains, NW-Spain. *Facies* 52, 149–167.

Julivert, M., 1971. Décollement tectonics in the Hercynian Cordillera of NW Spain. *American Journal Science* 270, 1–29.

Julivert, M., 1978. Hercynian orogeny and Carboniferous paleogeography in Northwestern Spain: A model of deformation–sedimentation relationships. *Zeitschrift der Deutschen Geologischen Gesellschaft* 129, 565–592.

Keller, M., 1988. Fazies, Paläogeography und synsedimentäre Tektonik im Unterdevon des Kantabrisches Gebirges (NW Spanien) [Facies, palaeogeography and synsedimentary tectonics in the Lower Devonian of the Cantabrian Mountains (NW Spain)]. *Erlanger Geologische Abhandlungen* 115, 77–115 (in German).

Keller, M., 1997. Evolution and sequence stratigraphy of an early Devonian carbonate ramp, Cantabrian Mountains, northern Spain. *Journal of Sedimentary Research* 67, 638–652.

Keller, M., Bahlburg, H. & Reuther, C.D., 2008. The transition from passive to active margin sedimentation in the Cantabrian Mountains, Northern Spain: Devonian or Carboniferous? *Tectonophysics* 461, 414–427.

Keller, M., Bahlburg, H., Reuther, C.D. & Weh, A., 2007. Flexural to broken foreland basin evolution as a result of Variscan collisional events in northwestern Spain. [In:] R.D. Hatcher, M.P. Carlson, J.H. McBride & J.R. Martínez Catalan (Eds): *4-D framework of the continental crust*. Geological Society of America, Memoir 200, 1–22.

Knight, J.A., Burger, K. & Brieg, G. 2000. The pyroclastic tonsteins of the Sabero Coalfield north-western Spain, and their relationship to the stratigraphy and structural geology. *International Journal of Coal Geology* 44, 187–226.

Kullmann, J. & Schönenberg, R., 1975. Geodynamische und palökologische Entwicklung im Kantabrischen Variszikum (Nordspanien). Ein interdiziplinäres Arbeitskonzept [Geodynamic and palaecological evolution in the Variscan Cantabrian (Northern Spain). An interdisciplinary working concept]. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte* 3, 151–166 (in German, with English summary).

Lotze, F., 1945. Zur Gliederung der Varisziden in der Iberischen Meseta [On the classification of the Variscides in the Iberian Meseta]. *Geotektonischer Forschung* 6, 78–92 (in German).

Lotze, F., 1961. Das Kambrium Spaniens. Teil I, Stratigraphie [The Cambrian of Spain. Part I, Stratigraphy]. *Akademie der Wissenschaften und der Literatur, Abhandlungen der Mathematisch-Naturwissenschaftlichen* 6, 216 pp (in German).

Marcos, A., 1979. Facies differentiation caused by wrench deformation along a deep-seated fault system (León Line, Cantabrian Mountains, North Spain) – Discussion. T*ectonophysics* 60, 303–309.

Marcos, A. & Pulgar, F.J., 1982. An approach to the tectonostratigraphic evolution of Cantabrian thrusts and fold belt, Variscan Cordillera of NW Spain. *Neues Jahrbuch für Geologie und Paleontologie Abhandlungen* 163, 256–260.

Marquínez, J. & Marcos, A., 1984. La estructura de la unidad de Guildar-Montó (Cordillera Cantábria) [The structure of the Guildar-Montó unit (Cantabrian Mountains)]. *Trabajos de Geología* 14, 53–64 (in Spanish, with English summary).

Martin-Meríno, G., Fernández, L.P., Colmenero, J.R. & Bahamonde, J.R., 2014. Mass-transport deposition in a Variscan wedge-top foreland basin (Pisuerga area, Cantabrian Zone, NW Spain). *Marine Geology* 356, 71–87.

Matte, P., 1991. Accretionary history and crustal evolution of the Variscan belt in Western Europe. *Tectonophysics* 196, 309–337.

Navidad, M., Castiñeiras, P., Casas, J.M., Liesa, M., Belousova, E., Proenza, J. & Aiglsperger, T., 2018. Ordovician magmatism in the Eastern Pyrenees: implications for the geodynamic evolution of northern Gondwana. *Lithos* 314, 479–496.

Nijman, W. & Savage, J.F., 1989. Persistent basement wrenching as controlling mechanism of Variscan thin- skinned thrusting and sedimentation, Cantabrian Mountains Spain. *Tectonophysics* 169, 281–302.

Nijman, W. & Savage, J.F., 1991. Persistent basement wrenching as controlling mechanism of Variscan thin-skinned thrusting and sedimentation, Cantabrian Mountains Spain: reply. *Tectonophysics* 194, 177–182.

Pastor-Galán, D., Gutiérrez-Alonso, G., Fernández-Suárez, J., Murphy, J.B. & Nieto, F., 2013. Tectonic evolution of NW Iberia during the Paleozoic inferred from the geochemical record of detrital rocks in the Cantabrian Zone. *Lithos* 182-183, 211–228.

Pereira, M.F., Solá, A.R., Chichorro, M., Lopes, L., Gerdes, A. & Silva, J.B., 2012. North-Gondwana assembly, break-up and paleogeography: U–Pb isotope evidence from detrital and igneous zircons of Ediacaran and Cambrian rocks of SW Iberia. *Gondwana Research* 22, 866–881.

Pérez-Estaún, A., Bastida, F., Alonso, J.L., Marquínez, J., Aller, J., Álvarez-Marrón, J., Marcos, J. & Pulgar, J.A., 1988. A thin-skinned tectonics model for an arcuate fold and thrust belt: the Cantabrian Zone (Variscan Ibero-Armorican Arc). *Tectonics* 7, 517–537.

Pérez-Estaún, A. & Bea, F., 2004. Macizo Iberico [Iberian Massif] [In:] J.A. Vera, (Ed.): *Geología de España: Madrid* [*Geology of Spain: Madrid*]. Sociedad Geología de Espana, Instituto Geología y Minero Espana, 19–230 (in Spanish).

Radig, F., 1962. Ordovicium/Silurium und die Frage prävariszischer Faltungen in Nord-Spanien [Ordovician/Silurian and the question of pre-Variscan folds in northern Spain]. *Geologische Rundschau* 52, 346–457 (in German, with English summary).

Raven, J.G.M., 1983. Conodont biostratigraphy and depositional history of the Middle Devonian to Lower Carboniferous in the Cantabrian Zone (Cantabrian Mountains, Spain). *Leidse Geologische Mededelingen* 52, 265–339.

Reijers, T.J.A., 1972. Facies and diagenesis of the Portilla Limestone Formation between the river Esla and the Embalse de la Luna, Cantabrian Mountains, Spain. *Leidse Geologische Mededelingen* 47, 163–249.

Reijers, T.J.A., 1985. Evidence for strike-slip movements along the Sabero-Gordón and associated faults in the Luna-Porma area, Leon NW Spain. *Trabajos de Geología* 15, 177–187.

Reuther, C.D., 1977. Das Namur im südlichen Kantabrischen Gebirge (Nordspanien), Krustenbewegungen und Faziesdifferenzierungen im Übergang Geosynklinale–Orogen [The Namur in the southern Cantabrian Mountains (northern Spain), crustal movements and facies differentiation in the geosyncline-orogen transition]. *Clausthaler Geologischer Abhandlungen* 28, 122 pp (in German).

Ribeiro, A., Quesada, C. & Dallmeyer, R.D., 1990. Geodynamic evolution of the Iberian Massif. [In:] R.D. Dallmeyer & E.M. Garcia (Eds): Pre-Mesozoic Geology of Iberia. IGCP-Project 233. Springer, Berlin, Heidelberg, 397-409.

Rodríguez-Fernández, L.R., 1979. *Memoria. Mapa Geológico de España escala 1:50000, 76 (Pola de Somiedo) segunda serie*. Instituto Geológico y Minero de España, 51 pp.

Rodríguez-Fernández, L.R., 1993. Tectonosedimentary evolution of a Carboniferous foreland basin related with arcuated fold-thrust belts. The example of NW Iberian Variscan belt. *Comptes Rendus of the XII International Congress of the Carboniferous-Permian Stratigraphy and Geology, Buenos Aires* 1, 435–445

Rodríguez-Fernández, L.R., 1994. *Estratigrafía y estructura de la región de Fuentes Carrionas y áreas adyacentes (Cordillera Herciniana, NO de España)* [*Stratigraphy and structure of the Fuentes Carrionas region and adjacent areas (Cordillera Herciniana, NW Spain)*]. Laboratorio Xeolóxico de Laxe La Coruña Serie Nova Terra 9, 240 pp. (in Spanish).

Rodríguez-Fernández, L.R. & Heredia, N., 1988. Carboniferous stratigraphy and structure of the Pisuerga-Carrion unit. NW Spain. *Cuaderno Lab. Xeolóxico de Laxe Coruña* 12, 207–229.

Sanz-López, J., García-López, S. & Montesinos, J.R., 2000. Conodonts del Frasniense superior y Fameniense inferior de la formation Cardano (unidad del Gildar-Montó, dominio Palentino, zona Cantábrica) [Conodonts from the upper Frasnian and lower Famennian of the Cardano formation (Gildar-Montó unit, Palentino domain, Cantabrian zone)]. *Revista Espanola de Paleontología* 14, 25–35 (in Spanish, with English summary).

Sitter, L.U., 1962. The structure of the southern slope of the Cantabrian Mountains; explanation of a geological map with sections scale 1:100,000. *Leidse Geologische Mededelingen* 26, 255–264.

Sjerp, N., 1967. The Geology of the San-Isidro Porma area (Cantabrian Mountains, Spain). *Leidse Geologische Mededelingen* 39, 55–128.

Stampfli, G.M., Hochard, C., Vérard, C., Wilhem, C. & Von Raumer, J., 2013. The formation of Pangea. Tectonophysics 593, 1–19.

Stel, J.H., 1975. The influence of hurricanes upon the quiet depositional conditions in the Lower Emsian La Vid Shales of Colle (NW Spain). *Leidse Geologische Mededelingen* 49, 475–486.

Suarez de Centi, C.A., 1988. *Estratigrafía y sedimentología de la unidad Fm Furada/San Pedro (Silúrico superior-Devónico inferior), Zona Cantábrica, Cuenca Astur-Leonesa* [*Stratigraphy and sedimentology of the Furada/San Pedro Fm unit (Upper Silurian-Lower Devonian), Cantabrian Zone, Astur-Leonesa Basin*]. Madrid, Instituto Geológico y Minera, Informe 7, 530 pp. (in Spanish).

Ten Have, A.H.M., 1979. *Stratigrafie en facies van de Devonische Portilla kalksteen formatie in het Somiedo-Luna gebied, Cantabrisch Gebergte, NW Spanje* [*Stratigraphy and facies of the Devonian Portilla limestone formation in the Somiedo-Luna area, Cantabrian Mountains, NW Spain*]. Leiden University, Internal Report, 120 pp. (in Dutch).

Van Adrichem Boogaert, H.A., 1967. Devonian and Lower Carboniferous conodonts of the Cantabrian Mountains (Spain) and their stratigraphic application. *Leidse Geologische Mededelingen* 39, 129–192.

Van Loevezijn, G.B.S., 1983. Upper Devonian block movements and sedimentation in the Asturo-Leonese Basin (Cantabrian Mountains, Spain). Leidse Geologische Mededelingen 52, 185–192.

Van Loevezijn, G.B.S., 1986. Stratigraphy and facies of the Nocedo, Fueyo and Ermita formations (Upper Devonian to lowermost Carboniferous) in León, N Spain. *Scripta Geologica* 81, 1–116.

Van Loevezijn, G.B.S., 2020. Forebulge dynamics and sedimentary response of an initial Variscan foreland basin; the Upper Devonian of the southern Cantabrian Mountains, N Spain. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* 171, 249–276.

Van Loevezijn, G.B.S., 2022. Upper Devonian soft sediment deformation structures in Frasnian and Famennian tempestites and related sediments, Cantabrian Mountains, Spain. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* 173, 402–423.

Van Loevezijn, G.B.S. & Raven, J.G.M., 2017. Frasnian carbonate shoals and sequence stratigraphy of the Upper Devonian series from the southern Cantabrian Mountains, northern Spain. *Boletín Geológico y Minero de España* 128, 931–961.

Van Loevezijn, G.B.S. & Raven, J.G.M., 2020. Facies patterns and depositional processes of two Frasnian mixed siliciclastic-carbonate systems in the Cantabrian Mountains, NW Spain. *Geologos* 26, 1–23.

Van Loevezijn, G.B.S. & Raven, J.G.M., 2021. The Upper Devonian of the river Sil area: a stratigraphic correlation between León and Asturias, northern Spain. *Boletín Geológico y Minero de España* 132, 325–354.

Van Loevezijn, G.B.S. & Van Loevezijn Peña, A.L.M., 2017. Facies cycles and sequences in the Upper Devonian of the Bernesga area. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* 168, 313–339.

Van Veen, J., 1966. The tectonic and stratigraphic history of the Cardano area, Cantabrian Mountains, northwestern Spain. *Leidse Geologische Mededelingen* 35, 45–104.

Vera de la Puente, C.,1989. Revisión litoestratigráfica de los Grupos Rañeces y La Vid (Devónico Inferior de la Cuenca Astur-Leonesa) [Lithostratigraphic review of the Rañeces and La Vid Groups (Lower Devonian of the Astur-Leonesa Basin)]. *Trabajos de Geología* 18, 53–65 (in Spanish, with English summary).

Veselovsky, Z., 2004. Integrated numerical modeling of a polyhistory basin, southern Cantabrian Basin (Palaeozoic, NW Spain). *Neues Jahrbuch für Geologie und Paläontologie Monatshefte* 10, 599–612.

Weil, A.B., 2006. Kinematics of orocline tightening in the core of an ac: paleomagnetic analysis of the Ponga unit, Cantabrian Arc, northern Spain. *Tectonics* 25, 1–23.

Weil, A.B., Gutiérrez Alonso, G. & Conan, J., 2010. New time constraints on lithospheric-scale oroclinal bending of the Ibero-Armorican Arc: a paleomagnetic study of earliest Permian rocks from Iberia. *Journal of Geological Society* 167, 127–143.

Weil, A.B., Gutiérrez-Alonso, G. & Wicks, D., 2013. Investigating the kinematics of local thrust sheet rotation in the limb of an orocline: a paleomagnetic and structur-

al analysis of the Esla tectonic unit, Cantabrian–Asturian Arc, NW Iberia. *International Journal of Earth Science* 102, 43–60.
Wotte, T., 2009. Re-interpretation of a Lower–Middle Cambrian West Gondwanan ramp depositional system: a case study from the Cantabrian Zone (NW Spain). *Facies* 55, 473–487.

Manuscript submitted 15 March 2023
Revision accepted 6 June 2023