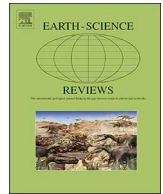




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New lithostratigraphy for the Cantabrian Mountains: A common tectono-stratigraphic evolution for the onset of the Alpine cycle in the W Pyrenean realm, N Spain

José López-Gómez^{a,*}, Fidel Martín-González^b, Nemesio Heredia^c, Raúl de la Horra^d, José F. Barrenechea^{a,e}, Patricia Cadenas^f, Manuel Juncal^g, José B. Diez^g, Violeta Borrueal-Abadía^{a,h}, David Pedreira^f, Joaquín García-Sansegundo^f, Pedro Farias^f, Carlos Galéⁱ, Marceliano Lagoⁱ, Teresa Ubide^j, Gabriela Fernández-Viejo^f, Georges Gand^k

^a Instituto de Geociencias, CSIC-UCM, C/ Doctor Severo Ochoa 7, 4, Universidad Complutense de Madrid, 28040 Madrid, Spain

^b Área de Geología-ESCEI, Universidad Rey Juan Carlos. C/ Tulipán, s/n, Móstoles, Madrid, 28933, Spain

^c Instituto Geológico y Minero de España (IGME). C/ Matemático Pedrayes 25, E33005 Oviedo, Spain

^d Departamento de Geodinámica, Estratigrafía y Paleontología, Facultad de Ciencias Geológicas, Universidad Complutense, C/ José Antonio Nováis 2, 28040, Madrid, Spain

^e Departamento de Mineralogía y Petrología, Facultad de Geología, Universidad Complutense, C/ José Antonio Nováis 2, 28040 Madrid, Spain

^f Departamento de Geología. Universidad de Oviedo. C/ Jesús Arias de Velasco s/n, E33005 Oviedo, Spain

^g Departamento de Xeociencias Mariñas e O.T. Facultade de Ciencias do Mar, Universidade de Vigo. Campus Lagoas-Marcosende, 36310 Vigo, Spain

^h Instituto Geológico y Minero de España (IGME), C/ Ríos Rosas 23, 28003 Madrid, Spain

ⁱ Universidad de Zaragoza, C/ Pedro Cerbuna 12, 50009 Zaragoza, Spain

^j School of Earth and Environmental Sciences. The University of Queensland. Steele Building. Brisbane, QLD 4072, Australia

^k Laboratoire Biogéosciences (UMR- CNRS/uB 6282), Université de Bourgogne, 6 Bd Gabriel, 21000 Dijon, France

ARTICLE INFO

Keywords:

Cantabrian Mountains
Pyrenees
Pyrenean-Cantabrian orogen
Alpine cycle
Permian-Triassic
Post-variscan tectonics

ABSTRACT

The Pyrenean-Cantabrian Orogen arose through the collision of the Iberian and Eurasian plates, mostly in Cenozoic times. This orogen comprises two main mountain ranges, the Pyrenees to the east, and the Cantabrian Mountains to the west. To date, the early Alpine tectono-sedimentary phases preserved in the Cantabrian Mountains, of Permian and Triassic age, have been considered independently from the same phases in neighbouring basins of SW Europe, and even from the eastern part of the same orogeny (the Pyrenean orogeny). In consequence, the beginning of the Alpine cycle in the Cantabrian Mountains has been interpreted within a specific geodynamic context, far from the general evolutionary phases of the western Peri-Tethys basins.

Through detailed field work, including geological mapping, sedimentology, lithostratigraphy and petrology of volcanic rocks, and new palaeontological data, here we define several new lithostratigraphical formations and five new tectono-sedimentary cycles (TS I-V) for the initial phases of evolution of the Mesozoic Basque-Cantabrian Basin, interrupted by periods of tectonic stability. To complete this information, we include data from an onshore borehole (Villabona Mine) and two offshore boreholes constrained by 2D reflection seismic profiles acquired in the North Iberian continental platform. The main tectono-sedimentary cycles, related to the deposition of five major identified lithostratigraphic units, can be described as follows:

TS I (late Gzelian-early Asselian), relating to the late Variscan deformation and preserved in a single outcrop in all the Cantabrian Mountains (San Tirso Formation). This formation is constituted by medium-distal alluvial fan deposits in which humid intervals predominate, forming some thin coal beds.

TS II (Asselian-Sakmarian), a post-Variscan extensional phase with associated calc-alkaline magmatism, represented by profuse volcanic and volcanosedimentary intercalations in the early Permian sedimentary basins (Acebal Formation) and small plutons in surrounding areas.

* Corresponding author.

E-mail addresses: jlopez@ucm.es (J. López-Gómez), fidel.martin@urjc.es (F. Martín-González), n.heredia@igme.es (N. Heredia), rhorra@ucm.es (R. de la Horra), barrenechea@ucm.es (J.F. Barrenechea), pcadenas@geol.uniovi.es (P. Cadenas), majuncal@uvigo.es (M. Juncal), jbdiez@uvigo.es (J.B. Diez), violeta.borrueal@igeo.ucm-csic.es (V. Borrueal-Abadía), david@geol.uniovi.es (D. Pedreira), jgsansegundo@uniovi.es (J. García-Sansegundo), pfarias@geol.uniovi.es (P. Farias), mlago@unizar.es (M. Lago), t.ubide@uq.edu.au (T. Ubide), gaby@geol.uniovi.es (G. Fernández-Viejo).

<https://doi.org/10.1016/j.earscirev.2018.11.008>

Received 17 July 2018; Received in revised form 13 November 2018; Accepted 13 November 2018

Available online 19 November 2018

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TS III (Kungurian), or reactivation of the post-Variscan extension leading to alluvial and lacustrine carbonate sedimentation in arid climate conditions, which do not change during the rest of the Permian and Triassic periods (Sotres Formation). A generalized karstification in the basin represents the end of Permian deposition, followed by an interruption in sedimentation longer than 30 Myr. The Permian tectono-sedimentary cycles (TS II and TS III) are contemporary with Variscan belt collapse and the basins are controlled by extensional re-activation of NE-SW and E-W Variscan structures, and NW-SE late Variscan structures.

TS IV (late Anisian–middle Carnian), renewed sedimentation in more extensive basins, precursors of the great Mesozoic Basque-Cantabrian Basin. This cycle is represented by fluvial deposits (Cicera Formation, or Buntsandstein facies), which are interrupted by the first Mesozoic marine ingression (Rueda Formation, or Muschelkalk facies).

TS V (Norian-Rhaetian), or shallow marine carbonate deposits (Transición Formation) related to increasingly compartmentalized sub-basins, controlled by normal faults. This final TS is broadly connected with different basins of the western Peri-Tethys domain.

The identification of units TS I-V in the Cantabrian Mountains along with the volcanic character of TS II, all indicate the development of a common post-Variscan to early Alpine tectono-sedimentary evolution for the whole Pyrenean-Cantabrian realm.

1. Introduction

The Cantabrian Mountains are the western extension of the Pyrenean-Cantabrian Orogen, uplifted during the orogenic phases of the Alpine Cycle in this area. In the Pyrenean-Cantabrian orogenic belt, the Alpine Cycle consists in an early Permian-Late Cretaceous pre-orogenic phase and a subsequent synorogenic phase, active between the Late Cretaceous and the Miocene. The Pyrenean-Cantabrian orogeny is the result of the collision between the Iberian and Eurasian plates, mostly in Cenozoic times. It comprises two main mountain ranges, the Pyrenees in the east, forming the isthmus between France and Spain, and the Cantabrian Mountains in the west, running parallel to the North Spanish coast of the southern Bay of Biscay (Pulgar et al., 1999; Gallastegui et al., 2002; Barnolas and Pujalte, 2004; Pedreira et al., 2007; Martín-González and Heredia, 2011a, 2011b) (Fig. 1a).

Today, the early tectono-sedimentary phases of the Alpine cycle in the Cantabrian Mountains of Permian and Triassic age, are considered an undifferentiated event, with rocks deposited in a single, large extensional basin, precursor of the great Mesozoic Basque-Cantabrian Basin. This overview arose from misinterpretation of some lithological formations due to the apparent continuity and similar red beds facies of both Permian and Triassic rocks, which have been jointly described and mapped as “Permian-Triassic rocks”. Further, the poorly preserved fossil contents and therefore uncertain age of the rocks, has led to the proliferation of works based on erroneous stratigraphic interpretations. As a result, many present-day Permian and Triassic lithostratigraphical formations have been erroneously aged or appear repeated with different names, or laterally correlated with areas where they were not deposited. Because of these stratigraphic issues, the lithostratigraphical formations, main sedimentary cycles, and tectonic and palaeogeographic evolution of the Permian and Triassic phases in the Cantabrian Mountains have not been well constrained. Indeed, the rocks the record preserved in these rocks is difficult to compare with other major sedimentary cycles of the same time-interval preserved in the Pyrenees and adjacent basins of the same age. Despite these challenges, over the 20th century, many basic, interesting studies focussed on mining served to sketch the first geological maps of the Permian and Triassic rocks. Major work in this field was conducted by Martínez-García (1981), García-Mondejar et al. (1986), Suárez-Rodríguez (1988). More recently, numerous synthesis studies have been carried out by Martínez-García, 1991a, 1991b, 1990), López-Gómez et al. (2002), Robles (2004) and Robles and Pujalte (2004). Only few palaeontological data, basically from Permian rocks, are described in Patac (1920), Wagner and Martínez-García (1982), Demathieu and Saiz De Omeñaca (1990), Mamet and Martínez-García (1995), Gand et al. (1997), Sopena et al. (2009) and Juncal et al. (2016). This scarcity of data led to investigations of tectono-sedimentary relationships in the past century (Jullivert, 1971; Alonso et al., 1996; García-Espina, 1997; Pulgar et al., 1999), as

weel as in recent active research (Rodríguez Fernández et al., 2002; Merino-Tomé et al., 2009; Martín-González and Heredia, 2011a, 2011b; Cámara, 2017; Cadenas et al., 2018).

We present a detailed stratigraphic and tectonostratigraphic study of the late Variscan and first Alpine evolutionary phases of the Cantabrian Mountains. We apply a multidisciplinary approach to the study of several new outcrops in the central Cantabrian Mountains, including a borehole. We undertake sedimentological and petrological analysis of sedimentary, volcanic and volcanosedimentary rocks. Based on new palaeontological data, we were able to characterize and date the Permian and Triassic lithostratigraphical formations. All these data make it possible to establish a comprehensive lateral control of these formations. Further, we use borehole-constrained 2D seismic reflection data, obtained for oil and gas exploration purposes offshore, to interpret the central and western parts of the North Iberian platform. Based on our new data obtained, we provide a new lithostratigraphical and tectonic model for the Permian-Triassic sedimentary record in the Cantabrian Mountains and discuss its main implications in the context of the whole Pyrenean-Cantabrian domain.

2. Geological setting

The study area comprises the central part of the Cantabrian Mountains (Fig. 1a, b), crossing, from E to W, the northern Spanish provinces of Santander and Asturias and also the northern regions of Palencia and León. The area includes the highest summits of the Cantabrian Mountains, with several peaks exceeding 2600 m.

The Cantabrian Mountains represent the western part of the Pyrenean-Cantabrian orogen. According to the geological subdivision of the Cantabrian Mountains proposed by Martín-González and Heredia (2011a), the study area is flanked by the Vasco-Cantábrica Region in the east and the Astur-Galaica Region in the west (Fig. 1a). The Vasco-Cantábrica Region is characterized by a thick and complete succession of Triassic to Cretaceous sediments deposited in a complex and highly subsident Mesozoic extensional basin showing episodic volcanism (Ubide et al., 2014) –the Basque-Cantabrian Basin–. Mesozoic extensional structures were partially inverted during the Alpine compression regime (García-Espina, 1997; Pulgar et al., 1999) and the Mesozoic succession is locally detached above the Keuper facies' evaporites (e.g. Carola et al., 2015; Cámara, 2017). To the south, these Mesozoic sediments overthrust the Cenozoic synorogenic sediments of the Ebro and Duero foreland basins. In contrast, in the Astur-Galaica Region, Mesozoic sediments are absent or scarce; only in the eastern part of this region does a thin, fairly complete sequence crop out, corresponding to the so-called Gijón-Ribadesella Basin (e.g., Suárez-Rodríguez, 1988) or Asturian Basin (e.g., Lepvrier and Martínez-García, 1990; Uzkeda et al., 2016). The so-called Asturian Basin (Fig. 1b, c) can be considered the western extension of the Basque-Cantabrian Basin, since both are united

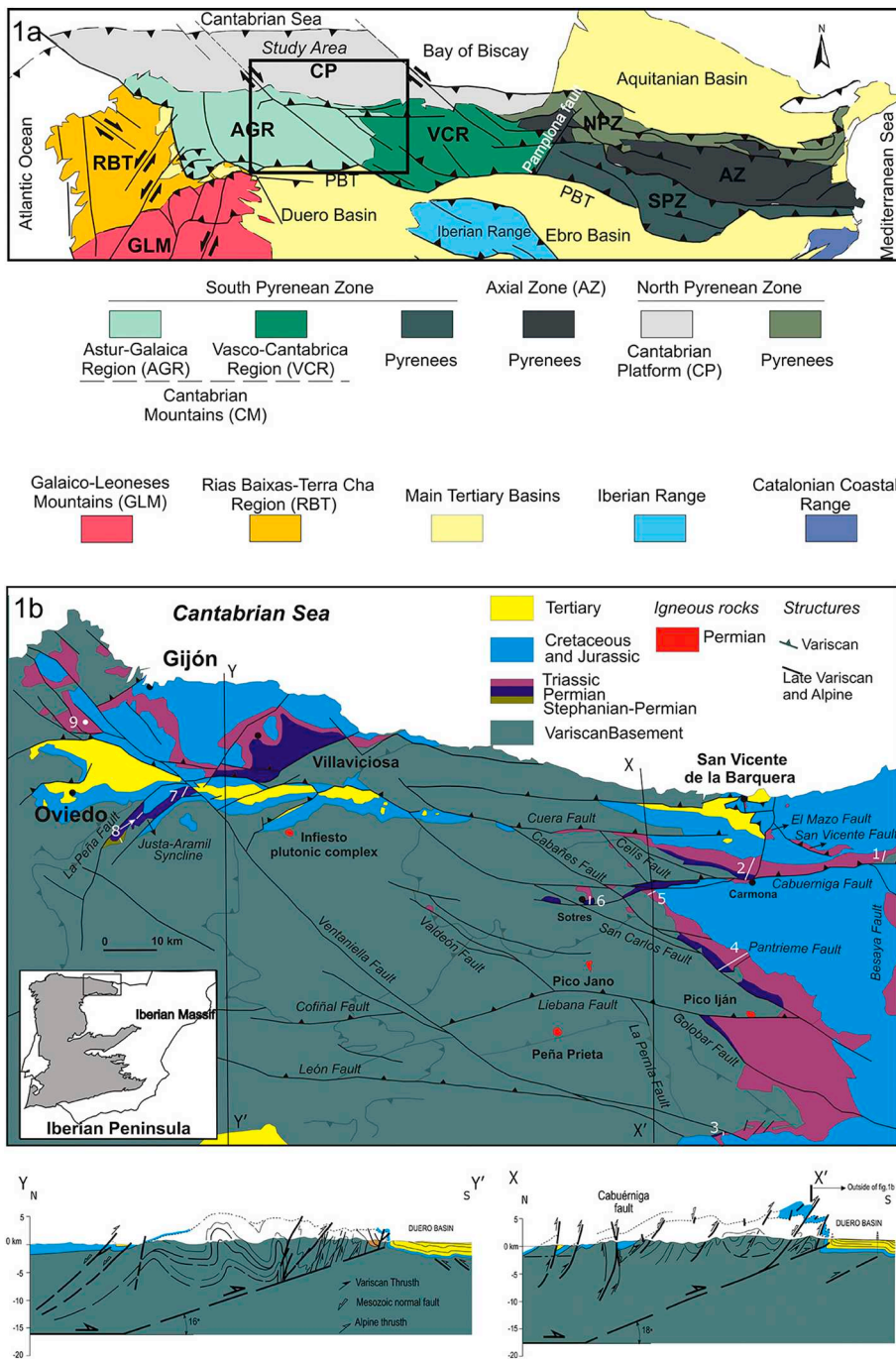


Fig. 1. a) Structural sketch showing the different tectono-stratigraphic regions of the Alpine Pyrenean-Cantabrian Orogen in the northern Iberian Peninsula (modified from Martín-González and Heredia, 2011). b) Simplified geological map of the central Cantabrian Mountains with the locations of the studied sections and localities. Studied sections: 1- Riocorvo, 2- Carmona, 3- Rueda, 4- Peña Sagra-Cohilla, 5- Cicera, 6- Sotres, 7- Acebal-Pola de Siero, 8- Frieres-San Tirso, 9- Villabona. See the sections in Fig. 4. Schematic geological cross-sections (X-X' and Y-Y') showing the Alpine structure of the central Cantabrian Mountains (Modified from Pulgar et al., 1999). Permian and Mesozoic rocks are not distinguished in the cross sections.

in the offshore. In the southern mountain front, a thin (< 1 km) Albian to Upper Cretaceous layer crops out in the forelimb of the fault-propagation fold created above the frontal thrust (Alonso et al., 1996). In this region, the Alpine compression deformation affects the Palaeozoic Variscan basement (Iberian Massif), strongly deformed in Carboniferous and earliest Permian times. The Alpine deformation reactivates some Variscan and Mesozoic structures, and the Mesozoic cover is undetached (Fig. 2a, b). Cenozoic synorogenic sediments filled small isolated depressions, generating a compartmentalized, broken foreland basin (Martín-González and Heredia, 2011b; Martín-González et al., 2014).

The Palaeozoic basement of the study area belongs to the foreland thrust and fold belt of the Variscan Orogen, which in this part of the Iberian Massif is known as the Cantabrian Zone (Lotze, 1945; Julivert et al., 1972). The main deformation related to the Variscan Orogen ends

in the latest Carboniferous and synorogenic sedimentation is well preserved in this zone (Julivert, 1971). The original Variscan structures were N–S trending along present-day coordinates, with general vergence to the east (Weil, 2006; Weil et al., 2016 and references therein). Subsequent N-S shortening between the early Kasimovian and early Gzhelian led the bending of the Variscan structures (highlighted by their arched traces in Fig. 2a) forming the Cantabrian Orocline in early Permian times (e.g. Gutiérrez Alonso et al., 2012). At this time, the eastern part of the Cantabrian Zone (Picos de Europa Thrust System, Fig. 2a) was emplaced towards the south (Merino-Tomé et al., 2009) and its syntectonic sediments were deposited in the Pisuerga-Carrión Province Region (Fig. 2a, b). This Province constitutes the foreland basin of the whole Cantabrian Zone (Rodríguez-Fernández and Heredia, 1987; Rodríguez Fernández et al., 2002). Finally, late Variscan faults developed at the Carboniferous-Permian boundary (Gzhelian-Asselian).

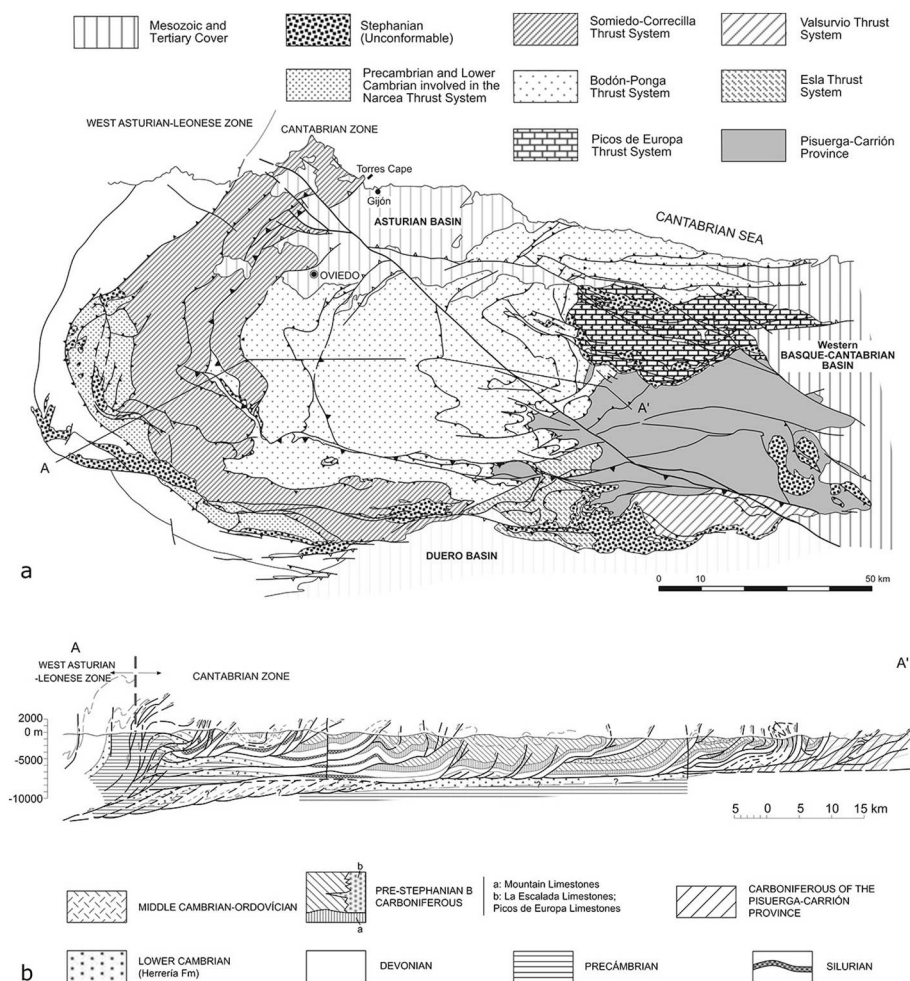


Fig. 2. a) Structural sketch of the Cantabrian Zone (Variscan orogenic belt) showing the western end of the Basque-Cantabrian Basin and the onshore Asturian Basin. Modified from [Alonso et al. \(2009\)](#). The Asturian sector is equivalent to the Asturian Basin, and the Palentine and Cantabrian sectors are located to the south and to the north, respectively. b) Geological cross section showing the Variscan structure of the Cantabrian Zone (Modified from [Aller et al., 2004](#)). Location of the cross section in [Fig. 2a](#).

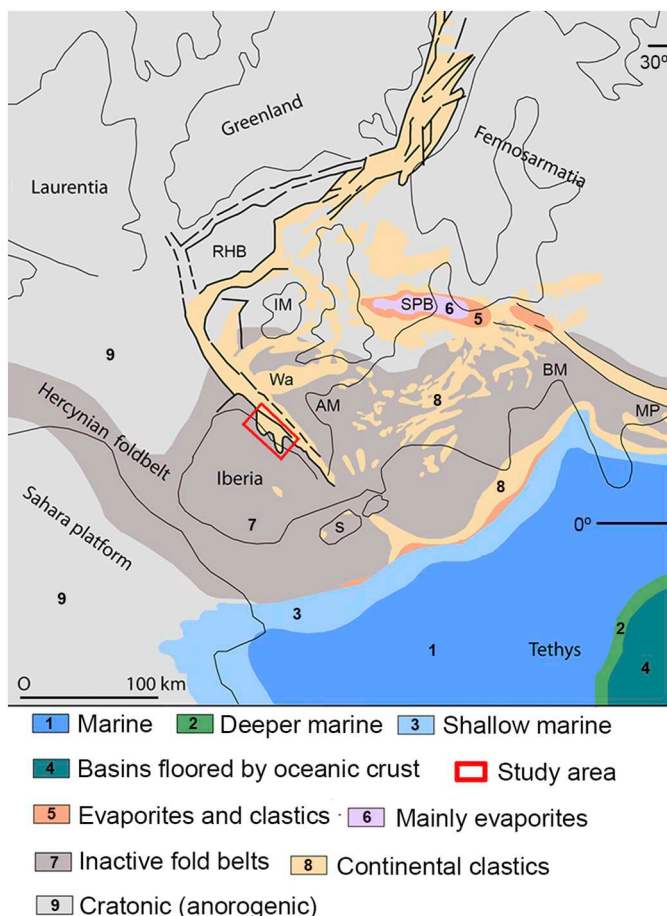
These faults, mostly NW-SE strike-slip faults (e.g., the Ventaniella fault of [Fig. 1a, b](#)), crosscut the Cantabrian Zone affecting Palaeozoic structures.

The Permo-Carboniferous tectonomagmatic pulse had a major impact on the crustal configuration of western and central Europe ([Ziegler and Dèzes, 2006](#)). Stephanian-early Permian lithosphere wrench deformation in these areas caused general reorganization of the mantle convection system. As result, upwelling of the asthenosphere induced thermal thinning of the mantle-lithosphere and magmatic inflation of the remnant lithosphere accompanied by regional uplift ([Ziegler and Stampfli, 2001](#)). At the end of early Permian, isolated basins developed in western and central Europe ([Fig. 3](#)), and later generalized thermal relaxation of the lithosphere in these zones during the late Permian and Early-Middle Triassic allowed westward propagation of the Tethys rift system ([Stampfli and Kozur, 2006](#)).

However, this orogenic collapse was not generalized in the Cantabrian Zone, since it corresponded to the foreland of the orogen, where the crust had thickened less ([Pérez-Estaún et al., 1991](#)). This extensional collapse was accompanied by the development of narrow, isolated basins. These basins were controlled by reactivation of Variscan and late Variscan structures. Source areas were close and remained active throughout the Cisuralian (early Permian).

The Triassic intracontinental extension must be associated with the onset of the northern Pangea break-up ([Salas and Casas, 1993](#); [Juez-Larré and Ter Voorde, 2009](#)) that generally started in late Permian times

([Ziegler and Stampfli, 2001](#)) including the Iberian Peninsula ([Sánchez-Martínez et al., 2012](#)). In earliest Permian times this event generated the continental basins, NW-SE elongated and much more extensive than the Permian basins and with more remote source areas ([Sánchez-Martínez et al., 2012](#)). This rifting event ended in the Late Triassic-Early Jurassic (e.g. [Ziegler, 1993](#)). In the study area, a subsequent Late Jurassic to Early Cretaceous rifting period gave rise to the opening of the Bay of Biscay, which individualized the Iberian and the European plates ([Boillot et al., 1979](#); [Derégnaucourt and Boillot, 1982](#); [García-Espina, 1997](#); [Roest and Srivastava, 1991](#); [Thinon et al., 2003](#); [Sibuet et al., 2004](#); [Tugend et al., 2014](#); [Cadenas et al., 2018](#)). Later on, a change to a convergent setting between the Iberian subplate and the European plate in the framework of the Alpine Orogeny led to the uplift of the Pyrenean-Cantabrian orogen along the Iberian/European plate boundary (e.g., [Vergès and García-Senz, 2001](#); [Pedreira et al., 2007](#); [Roca et al., 2011](#); [Martín-González and Heredia, 2011a, 2011b](#); [Teixell et al., 2018](#)). Many of the former Variscan, late-Variscan and Mesozoic faults were reactivated/inverted during this orogenic event ([Fig. 1a](#)). The central Cantabrian Mountains uplift was essentially produced by thrusting developed over a long frontal ramp connected to a midcrustal detachment ([Alonso et al., 1996](#)). Here, the main episode of uplifting (responsible for the present-day relief) was late Eocene-early Oligocene in age ([Martín-González et al., 2012, 2014](#); [Fillon et al., 2016](#)), lasting until latest Miocene times towards the western border of the range ([Martín-González et al., 2014](#); [Martín-González and Heredia, 2011b](#) and references therein).



RHB- Rockall-Hatton Bank, IM- Irish Massif, BM- Bohemian Massif
EA- West Approaches Trough, SPB- Southern Permian Basin, MP- Moesian Platform, WA- Western Approaches trough, AM- Armorican Massif

Fig. 3. Palaeogeographic sketch of eastern equatorial Pangea for the early-middle Permian transition. The studied area is marked with a red square. Modified from Ziegler (1988). Palaeolatitudinal data obtained from Ziegler (1993). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Methods

Most of our work was based on the reconstruction and sedimentary interpretation of eight representative stratigraphic sections in the field. Their selection was based on preliminary detailed geological mapping and tectonic study to avoid repetitions due to faults and thrusts (Fig. 1b). To compare these sections with previous (classic) works, the geographic Asturian, Cantabrian and Palentine areas are also represented here in some figures. The first of these areas are onshore zones of the Asturias Basin, and the remaining two are the north and south domains of the western Basque-Cantabrian Basin, respectively. Stratigraphic sections were chosen as representative of these three main stratigraphic areas of the Cantabrian Mountains. In central Asturias, in Villabona, north of Oviedo, where the vegetation cover hinders detailed fieldwork, a borehole (cuN-69B) obtained by courtesy of the MINERSA Group, allowed for a detailed study of the Permian-Triassic succession in this zone. The well is 674 m deep and shows 342 m of Permian and Triassic rocks.

In the 8 stratigraphic sections and the MINERSA borehole (Figs. 4, 5), we defined different facies and their associations, and 15 architectural elements representing the different depositional environments. To establish affinities of the associated volcanism and their relationships with the differentiated tectono-sedimentary pulses, mineral

assemblages and rock textures were examined in a petrographic study of 24 samples from the Acebal section.

Because of the scarcity of available data, we estimated the age of the studied lithostratigraphical formations according to palaeontological criteria. Nine new pollen assemblages obtained from nine different levels, fossil plants and footprints were collected and analysed, and these were complemented with samples recently examined by members of our research group (Juncal et al., 2016). Palynological samples were processed using HCl-HF-HCl attack techniques as described by Wood et al. (1996). Prepared samples on thin-sections were studied under a Leica DM 2000 LED, and final selected photos were taken with a Leica ICC50 W camera.

In addition to the fossil plant found in this work, a macroflora bibliographic compilation of all studies carried out in the study area was done in order to enhance the works published until today. Unfortunately, in most of these publications, the number of specimens that integrate these collections is not provided.

In this work, the scarcity of footprints only allowed to compare them with other specimens of ichnogenus using photographs from other works, therefore, no morphological nor biometrical methods have been used.

For a more complete study of Permian and Triassic sedimentary remnants in the northern Iberian Peninsula, structural fieldwork was carried out on the western side of the Basque-Cantabrian Basin, with special emphasis placed on determining the relationships between faults, their age, and their role in controlling Permian and Triassic deposition. For the sake of completeness, we also examined the stratigraphic records of two boreholes and 2D seismic reflection profiles offshore in the continental platform of the North Iberian margin: borehole Galicia-B2, drilled by Chevron in 1977, and borehole Mar Cantábrico-K1, drilled by Shell in 1978 (borehole reports from Lanaja, 1987; Gutiérrez-Claverol and Gallastegui, 2002 and Cadenas and Fernández-Viejo, 2017).

4. The Permian-Triassic stratigraphical formations

The Permian and Triassic stratigraphy of the Cantabrian Mountains has been traditionally studied in three main sectors, broadly coincident with the geographic provinces in which this sedimentary record appears: Asturian, Cantabrian and Palentine sectors (Fig. 1a, b). Thereby, the general description of the stratigraphic units of the Cantabrian Mountains has been traditionally separated in different successions related to these areas. Subsequent studies defined numerous lithostratigraphical units and subunits (e.g. Suárez-Rodríguez, 1988, for the Asturian area, and Martínez-García, 1990, for the Cantabrian and Palentine areas), of local validity in some cases (Table 1). Although remarkable efforts have been made to correlate these units among the different areas (e.g. Martínez-García, 1991a, 1991b; Gand et al., 1997; Martínez-García et al., 2001), the scarcity of palaeontological or radiometric data has hindered detailed correlations (López-Gómez et al., 2002). Moreover, some of the units have been erroneously correlated based only on lithological characteristics, such as the Arroyo and Sotres formations, or the Sagra and Caravia formations (Gand et al., 1997). Between the Sotres and Caravia formations, Martínez-García et al. (1991a, b) described the Cabranes Formation, also of early Permian age. Once again, this was only of local validity as it was based on lithological criteria alone and the unit was correlated with the Paraes and La Cuesta formations, described in the Peña Sagra area (Gand et al., 1997).

The Caravia Formation, as discussed later, represents a clear example of erroneous assignment. Its age has been interpreted as both early and late Permian (Martínez-García, 1991a, 1991b) in the absence of palaeontological criteria. Moreover, the formation was correlated with other units of different areas in the Cantabrian Mountains (Gand et al., 1997), and even with Permian units in the Iberian Ranges (Martínez-García, 1991b), over 400 km away, in Central Spain.

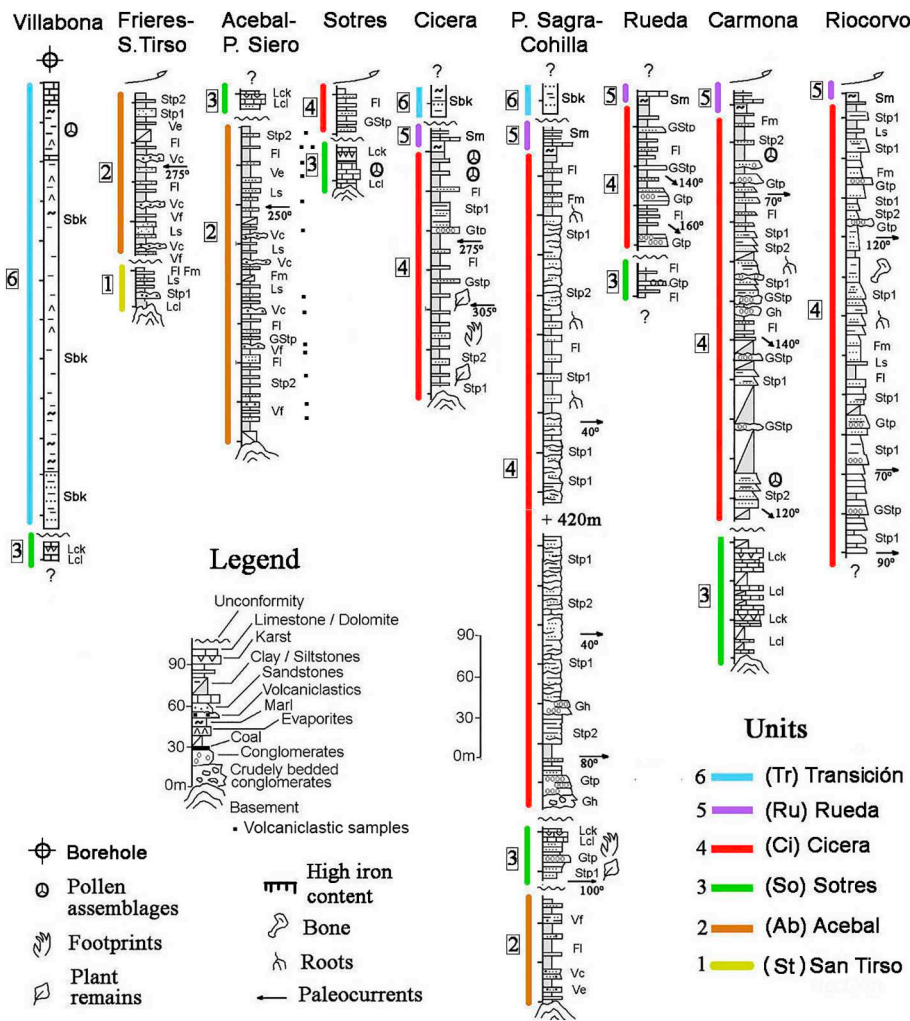


Fig. 4. Studied stratigraphic sections and log of the Villabona borehole. Sections include differentiated lithostratigraphical units, architectural elements (abbreviations refer to Fig. 7) and locations of our palaeontological data (see also Table 2 for more detailed location of the palaeontological data in the studied sections and the different formations). See Fig. 1b for the location of the sections. Geographical location of the sections: Villabona: 43°27'50", 5°50'18"; Frieres: 43°20'40", 5°44'20"; Acebal: 43°19'40", 5°42'20"; Sotres: 43°14'09", 4°44'18"; Cicera: 43°14'10", 4°34'12"; Peña Sagra: 43°02'18", 4°26'15"; Rueda: 42°51'30", 4°24'40"; Carmona: 43°16'50", 4°20'18"; Riocorvo: 43°16'12", 3°54'12".

However, as discussed below, various pollen assemblages (this work) indicate a late Anisian-early Carnian (Middle-Upper Triassic) age for what has been considered the Caravia Formation in most of previous studies. Despite the initial lack of sufficient palaeontological criteria to define an accurate lithostratigraphical succession for the Permian and the Triassic sedimentary record in the Cantabrian Mountains, interesting sedimentary descriptions are available, mainly for the Triassic records in the Cantabrian area (e.g., Smit, 1966; Saiz de Omeñaca, 1977; García-Mondejar et al., 1986, among others). The whole Triassic succession was named the Nansa Group by Maas (1974), including the classic Buntsandstein, Muschelkalk and Keuper facies.

The Sotres, Peña Sagra-Cohilla and Riocorvo stratigraphic sections have been described in the mentioned contributions, while the Villabona, Cicera, Carmona, Frieres, Acebal-Pola de Siero and Rueda sections, as well as the Villabona borehole (Figs. 1b, 5) are firstly described in this work.

To follow the International Stratigraphic Guide's recommendations, we have tried to keep the same names as defined by other authors as much as possible, although most original stratigraphic locations have now been changed based on the new palaeontological data. All units have a stratigraphic rank of formation. Other units that have not been formally described, or units that were erroneously repeated, are given different names and stratigraphic locations. From base to top, the formations we describe here are: San Tirso (St), Acebal (Ab), Sotres (So), Cicera (Ci), Rueda (Ru) and Transición (Tr) (Fig. 4). The San Tirso formation is Carboniferous-Permian in age, the Acebal and Sotres units are Permian and Cicera, Rueda and Transición formations are Triassic.

Although most of the sections described lie directly on the basement and were chosen as the most complete in the areas examined, none of them show a complete vertical succession that includes all the units, with the Triassic sedimentary record eventually lying directly on the basement (Fig. 6a).

The main characteristics of each of these six formations are:

4.1. San Tirso Formation

The San Tirso Formation rests unconformably on the basement and is covered, also unconformably, by the Acebal Formation. This formation is comprised of sandstones, conglomerates and lutites and has interbedded, small coal beds in the basal part. This formation only appears in an isolated small basin that crops out in the southern part of the La Justa-Aramil Alpine syncline (Fig. 1b).

The formation was first described by Velando et al. (1975) and ascribed an uncertain age between the uppermost Kasimovian (upper Stephanian C) and the Permian (Autunian) (Wagner and Martínez-García, 1982). Later it was included in the Mestas de Con Formation by Martínez-García et al. (2001). Subsequent to this and according to more refined dates, Merino-Tomé et al. (2009) included the Mestas de Con Formation within the previously defined Cavandi Formation (Martínez-García, 1981). In the present study, we provide a different definition of the San Tirso Formation to Velando et al. (1975), as these authors included our Permian Acebal Formation within the top of this formation. Further, we separate the San Tirso Formation from the Mestas de Con/Cavandi Formation based on its distinctive age and tectonic and



Fig. 5. Partial section (664.3 m to 668.9 m) of the lithologic log from Villabona Mine (Courtesy of the Minersa Group). This part of the section represents the karst on the top of the Sotres Formation. Lateral equivalents to the karst are shown in Peña Careses, east Oviedo (Fig. 6B), and in the Carmona section (Fig. 9i). Vertical (red) lines mark some levels of breccias originated by dissolution (karstification). Part of the karst in the lithologic log is mineralized with fluorite, being this mineral the main objective of the exploration in the mine. Total thickness of the Sotres Formation in the lithologic log from Villabona Mine reaches 7.10 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stratigraphic features. Thus, the Mestas de Con/Cavandi Formation is a marine (mainly turbidites) Late Carboniferous (late Kasimovian/early Gzelian) synorogenic succession (Merino-Tomé, 2004; Merino-Tomé et al., 2006, 2007, 2009), which is intensely deformed by the Variscan Orogeny. In contrast, the San Tirso Formation is a latest Carboniferous-earliest Permian (late Gzelian-early Asselian) continental succession (Fig. 4), slightly deformed by the Variscan orogeny (late-orogenic succession) and unconformably overlying the remaining Carboniferous rocks of the Variscan Cantabrian Zone.

4.2. Acebal Formation

This unit is described here for the first time. Its section has been described near Acebal village (Asturian area), where it is 310 m thick, although the unit shows considerable lateral thickness variation. It lies unconformably on the underlying unit or directly on the basement. It basically consists of green volcanic and volcanoclastic rocks, red to green, medium- to coarse-grained sandstones, and red lutites. So far, these rocks have not been precisely dated, and their age attribution is here based on indirect criteria.

4.3. Sotres Formation

This formation was described by Martínez-García (1981) near the village of Sotres (Fig. 1b). Later, the same author (1991a) considered the Sotres Formation as one of the three units making up the Permian “post-Hercynian” (post-Variscan) sedimentary record, represented by the Sotres, Cabranes and Caravia formations. Following the criteria of

this author, the two first formations comprised the Viñón Group, while the latter was equivalent to the Villaviciosa Group. The Sotres Formation lies unconformably on the Mestas de Con Formation (Martínez-García, 1991a, 1991b), the Acebal Formation or directly on the basement. This latter author, and previously Wagner and Martínez-García (1982), described this unit as an 8 m-thick sequence of volcanoclastic beds, thin coal seam layers, and up to 90 m thickness of alternating gray limestones and black shales with volcanic debris. These same authors considered this formation could be as thick as 600 m in the Villaviciosa area. In our study, its total thickness appeared reduced up to 134 m in the Carmona area. In other sections (e.g., Peña Sagra-Cohilla and sections, Fig. 1b) this formation is composed of fine- to medium-grained sandstones in its lower part, and carbonate beds towards the top, where a large karst surface frequently develops (Fig. 6b).

4.4. Cicera Formation

This formation, described here for the first time, is located near the village of Cicera (Cantabrian area; Fig. 1b), where it is 180 m thick, although it shows substantial lateral thickness changes. The Cicera Formation rests unconformably on different previous units, or directly on the basement (Fig. 6a). It represents the classical Triassic “Buntsandstein facies”, as García-Mondejar et al. (1986) and Robles and Pujalte (2004) described in La Cohilla section, located in the upper part of our Peña-Sagra-La Cohilla section (Fig. 1b). The Cicera Formation consists of alternating red, fine- to coarse-grained sandstones and dark red lutites. These sandstones are more frequent in the lower half of the unit, where thin rounded-clast conglomerate layers may also appear. The unit, however, has been often described as the Caravia Formation in different areas (or Villaviciosa beds in eastern Asturian Basin, e.g., Wagner and Martínez García, 1982), and considered lower or upper Permian (Wagner and Martínez-García, 1982; Martínez-García, 1991a, 1991b; Martínez-García et al., 1991a; Mamet and Martínez-García, 1995; Martínez-García et al., 2001, among others). This misinterpretation has led to erroneous considerations when describing new stratigraphic units, e.g. correlating the well-dated early Permian Sagra Formation with the Caravia Formation (Gand et al., 1997), or even establishing equivalences between the Caravia Formation and other Permian units of Iberia and SW Europe (Martínez-García, 1991b).

4.5. Rueda Formation

This unit, is also described here for the first time. The section was established near the locality of Rueda (Palentine area), where it reaches a thickness of 3.5 m. It consists of gray and green marls in the lower part and ochre limestones and dolomites at the top. The unit is apparently transitional with the underlying Cicera Formation, whose sediments interrupt it. Thrusts usually affect the upper sedimentary record of this unit.

4.6. Transición Formation

The name of this unit makes reference to the “transition” from the Upper Triassic to the Lower Jurassic sedimentary record. It was first defined as “Tramo de Transición” (transition section) by Suárez-Vega (1969, 1974) near Villaviciosa (Fig. 1b). Later, Suárez-Rodríguez (1988) and Manjón et al. (1992) described it as Fuentes Unit and “Conjunto Superior”, respectively, which were likely parts of the same facies in closeby areas. The unit mostly consists of red marls and from base to top has intercalated red sandstone, gypsum beds and limestone. Due to its changing character, it often shows an incomplete sedimentary record, and many reports have approached its age according to palaeontological data (e.g., Martínez-García et al., 1998; De la Horra et al., 2012). Its thickness is difficult to estimate, but based on boreholes studies (Pieren et al., 1995, and this work's Fig. 4), we propose a variable thickness of 320 to 610 m. The unit rapidly loses thickness and

Table 1

Summary of classic lithological units described in the study area by previous authors (left and centre) and the new units described in the present work (right). Numbers represent references with supporting data: 1- Martínez-García et al. (1998); 2- Suárez-Vega (1974); 3- Martínez-García (1981); 4- Martínez-García (1991a); 5- Martínez-García (1991b); 6- De la Horra et al. (2012); 7- Manjón and Gutiérrez-Claverol (1991); 8- Martínez-García, 1991a, 1991b; 9- Martínez-García et al. (2001); 10- Wagner and Martínez-García (1982); 11- Gand et al. (1997); 12- Maas (1974); 13- García-Mondejar et al. (1986); 14- Robles and Pujalte (2004); 15- Robles (2004); 16- Martínez-García (2004).

		Cantabrian Mountains					
		Asturian	Cantabrian / Palentine	Proposed units			
Jurassic	T r i a s s i c	Transición Unit (1,2,6,7)	Keuper	Transición Unit			
					Nansa Unit (12,13,14)	Muschelkalk	Rueda Unit
							Cicera Unit
Early	Buntsandstein						
Permian	P e r m i a n	Caravia Fm (1,3,4,5)	Sagra Fm Cuesta Fm Paraes Fm Arroyo Fm (5,11)	Sotres Fm			
		Cabranes Fm —(4,5,7,16)→		(4,11,15)	Acebal Unit		
		Sotres Fm —(5,6)→			San Tirso Fm		
Carb	L a t e	San Tirso / Mestas de Con (8, 9, 10)					

disappears eventually towards the S, SE and E. It lies on different units, but always after an interruption in sedimentation.

5. Sedimentology

Sedimentological studies of the Permian and Triassic rocks in this part of the Cantabrian Mountains have yielded poor results. A few exceptions (e.g., García-Mondejar et al., 1986) have focused on the sedimentology of Triassic continental deposits. Most prior reports describe the sedimentary record mostly in terms of their lithological composition, but lack detailed sedimentary interpretations. The present study thus provides the first comprehensive sedimentary analysis and interpretation of the studied units. Our analysis is based on facies differentiation in all the described series. The associations of these facies allow us to define architectural elements. An architectural element was defined by Miall (1985) as a component of a depositional system of a river equivalent in size to, or smaller than a channel fill, and larger than individual facies unit, characterized by a

distinctive facies assemblage, internal geometry, external form and, in some instances, vertical profile. Fluvial facies and architectural elements have been mostly based on Miall's (1996, 2014) description and classification, while new codes have been adopted here for sediments of lacustrine, volcanoclastic and marine origin. The interpretation of the sedimentary environments and their vertical evolution in each defined unit is based on assigning these facies associations and architectural elements to the units.

In total, we describe 15 architectural elements and interpret them according to their facies and facies associations (Fig. 7). Of these, 7 are of fluvial origin, 3 of lacustrine and playa-lake origin, 3 of volcanoclastic origin, 2 of shallow marine origin and 1 of sabkha origin. Fig. 8 includes the descriptions and interpretations of these elements with indication of the sections in which they were identified. The precise positions of the architectural elements in all the sections are detailed in Fig. 4 while some of the main representative elements observed in the field can be seen in Fig. 8. We describe the architectural elements identified in each of the stratigraphic units defined as follow:

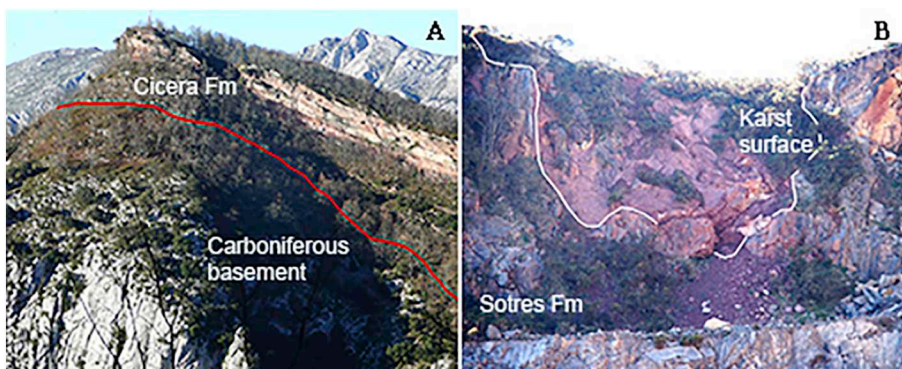


Fig. 6. A) Cicera Formation (late Middle to early Late Triassic) lying unconformably on the marine Carboniferous basement of the Cicera section. The lateral thickness changes of this formation are very important in this area. This formation is defined here for the first time and its age obtained by means of palynological assemblages. B) Karstification on the top of the Sotres Formation, in Peña Careses, east Oviedo. The picture is taken in a quarry where internal mineralization of the formation is obtained.


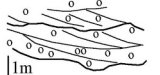
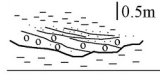
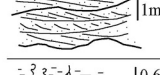
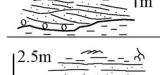

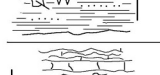
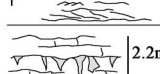



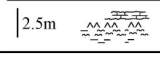
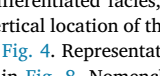
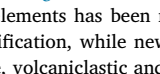
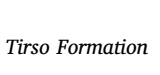
Origin	Code	Architectural element and Facies associations	Description (facies)	Interpretation	Location (Sections)
Fluvial	Gh	 0.3m	Clast-supported. Crudely bedded gravel and imbrication.	Longitudinal bedforms. Sieve deposits.	La Cohilla Peña Sagra
	Gtp	 1m	Clastic supported bedded gravel. Trough and planar cross-beds.	Gravel bars and bedforms in minor fluvial channel fill.	Cohilla Rueda Carmona Peña Sagra
	GStp	 0.5m	Sand, fine to very coarse and pebbly with trough and planar cross-beds	Mixed sinuous-crested linguoid (2D-3D) dunes in fluvial channels fill.	Riocorvo Rueda Cicera Carmona
	Stp1	 1m	Fine to coarse sand with planar and trough cross-beds	Sand bedform 1 Sandy sinuous-crested dunes in channel fill	Riocorvo Rueda, Cicera Cohilla Acebal
	Stp2	 0.6m	Fine to coarse sand and pebbles with cross-beds. Massive mud-silt with bioturbation and roots.	Sand bedform 2 Sandy sinuous crested dunes in channel fill and its abandoned body.	Riocorvo, Rueda Cicera, Cohilla Acebal, Carmona
	Fl	 2.5m	Fine sand with lamination and ripples into massive mud-silt deposits with roots.	Laminated sand into overbank fines. Overbank-waning flood deposits	Peña Sagra, Cicera Riocorvo, Rueda Acebal, Carmona Cohilla
	Fm	 2.5m	Massive mud-silt with desiccation cracks and roots (sometimes eroded)	Overbank-abandoned channel	Cicera, Rueda, Acebal, Cohilla Carmona
Lacustrine and plays lake	Ls	 2.5m	Fine laminated sand and silt with desiccation cracks and plant remains	Laminated sand and silt of accumulated plays deposits.	Rueda Acebal Carmona
	Lc1	 2.5m	Fine-medium laminated (ondulated-organic) grey carbonate lamina on green massive marls.	Laminated carbonates and marls. Accumulated lacustrine deposits	Peña Sagra Carmona
	Lck	 2.2m	Medium-thick laminated strata grey carbonate with karst carbonate	Karst into laminated carbonates Interruption and karstification of lacustrine deposits	Carmona
Volcaniclastic	Vf	 0.6m	Graded pyroclastic lapilli-breccia deposits	Pyroclastic airfall Fall-out of volcanic fragments (tephra)	Friera Acebal
	Vc	 1m	Medium to thick structureless. Possible reverse graded	Pyroclastic flow Turbulent flow of volcanic debris	Friera Acebal
	Ve	 0.3m	Reworking of volcanoclastic material with soft structure	Epiclastic flow. Mostly fluvial transported	Friera Acebal
Shallow marine	Sm	 0.6m	Succession of marls and limestones with ripples and algal lamination, and siltstones	Shallow marine. Inter-supratidal. Mixed sediments.	Cicera, Rueda, Cohilla, Carmona
Sabkha	Sbk	 2.5m	Successions of poorly organized siltstones, marls, gypsum and limestones beds	Marine sabkha. Transitional area. Mixed sediments.	Cicera, Cohilla, Villabona

Fig. 7. Differentiated facies, facies associations and defined architectural elements. Vertical location of the architectural elements in the studied sections are shown in Fig. 4. Representative field pictures of the architectural elements are provided in Fig. 8. Nomenclature of the facies, facies associations and architectural elements has been mainly based on Miall's (1996, 2014) description and classification, while new codes have been adopted here for sediments of lacustrine, volcanoclastic and marine origin.

5.1. San Tirso Formation

This formation includes elements GStp, Stp1, Lc1, Ls and Fl (Fig. 8 m, n) interpreted as arising from the migration of linguoid dunes in fluvial channels related to distal alluvial fans, and overbank waning flood deposits with humid intervals when fine-bed coal deposits accumulated. It is generally composed of fining-upwards sequences thinner than 2.3 m thick where the uppermost part may be represented by marly lacustrine deposits or sandy to silty laminae of playa-lake deposits. This unit was deposited in an isolated small basin (Fig. 1b).

5.2. Acebal Formation

This formation includes elements Vf, Vc, Ve, Vf, Fl, Ls, Fm, Stp2 and GStp. Essentially, the formation consists of different types of volcanoclastic deposits accumulated during successive pulses (Fig. 8 j, k, l), similar to examples described by Lago et al. (2004a, 2004b) and Perini and Timmerman (2008) in the eastern Pyrenees and Iberian Ranges. Interruption between volcanic pulses allowed for the development of small, mixed sandy and gravelly, braided fluvial systems with huge floodplain deposits in which roots and palaeosols developed. The

Acebal Formation was deposited in small, isolated basins bounded by active normal faults and (like in the rest of the Permian-Triassic lithostratigraphic units) rocks of this Formation were formed in arid conditions.

5.3. Sotres Formation

This Formation is formed by elements Lc1, Lck, Fl, Stp1 and Gtp (Figs. 4, 7, 8 h). The formation records the development of small, mixed sandy and gravelly, braided fluvial systems with the build-up of fine deposits in floodplains. The sediments were overlain by the development of carbonate lakes (Fig. 8 h) that reached their main thickness in the central areas of the lakes (Kelts and Hsü, 1978; Cohen and Thouin, 1987). This latter phase of sedimentation was interrupted by exposure of the lake sediments and the development of various karst surfaces (Figs. 6 B, 12 i). Carbonated sediments of this formation were initially interpreted as marine deposits (Martínez-García, 1991a, 1991b; Martínez-García et al., 1991a) but later considered to be continental in origin due to the presence of sponge-bacterial bafflestones harbouring *Bevoacstria* and ostracods, and the absence of marine microfauna and microflora (Mamet and Martínez-García, 1995). This formation probably represents the first Permian stage in which connections between some of the small extensional basins were established.

5.4. Cicera Formation

This formation attains a greater thickness and shows a wider geographic distribution, probably reaching some hundred Km, than the previous units. It is comprised of the elements GStp, Gh, Gtp, Stp1, Stp2, Sm, Fl, Fm and Ls and generally shows a fining and thinning-upwards trend. It records the development of mixed sandy and gravelly braided fluvial systems in the lower part of the formation (Fig. 8 b, d). These systems progress to an increase in floodplain deposits in the middle part (Fig. 8 e), which are the dominant sediments in the upper part of the formation (Fig. 8 f, g). Similar examples have been described by Gulliford et al. (2017) in the lower Beaufort Group of South Africa. The lowermost part of this formation only appears in the Peña Sagra-La Cohilla section (Fig. 4), where it represents longitudinal bedforms and sieve deposits related to proximal areas at the basin border (Fig. 8 a). The uppermost part of this formation shows a transition with the overlying Rueda Formation, of shallow marine origin. This transition is indicated by the presence of *Plaesiodyctyon mosellanum* (Fig. 10, number 21), a fresh-water to shallow marine environment alga. The sedimentation of this formation indicates larger sedimentary basins, which developed in an active and generalized extensional context (García-Espina, 1997; Robles and Pujalte, 2004) with different pulses that allowed for deposition with considerable thickness variations. In addition, a complete sedimentary record was only deposited in the most subsident depocenters, as described in the Early-Middle Triassic red beds of the Iberian Basin by López-Gómez et al. (2002).

5.5. Rueda Formation

This formation is basically represented by element Sm (Fig. 8 o) and is interpreted as inter-supratidal, shallow-marine, mixed sediments, similar to the Middle-Upper Triassic shallow marine deposits described by Escudero-Mozo et al. (2015) on the island of Mallorca. The formation constitutes the first Mesozoic marine incursion in the ancient western Basque-Cantabrian intracontinental basin. It would represent a short incursion of the Tethys Sea that only reached the central and eastern continental areas of this basin.

5.6. Transición Formation

This formation is basically represented by the element Sbk. Its lithology and thickness may change depending on the area. In the



Fig. 8. Field pictures of representative architectural elements. A- Gh; b- Gtp; c- GStp; d- Stp1; e- Stp2; f- Fl; g- Fm; h- Lc1; i- Lck; j- Vf; k- Vc; l- Ve, m- Stp1, Fm; n- Lc1; Fl; o- Sm. See Fig. 7 for descriptions of the elements. Facies, facies associations and architectural elements nomenclature has been mainly based on Miall's (1996, 2014) description and classification, while new codes have been adopted here for sediments of lacustrine, volcanoclastic and marine origin.

Villabona borehole, it sometimes reaches a thickness of hundreds of metres. However, due to tectonics, only isolated remnants under a few tens of metres crop out. In the Villabona borehole, marls, gypsum and dolomites tend to be the dominant lithologies upwards. This formation is interpreted as a continental-marine, transition environment at its base, evolving to marine sabkha deposits in its middle and upper parts. The dominant dolomite beds at the top of this formation are of Lower Jurassic age (Barrón et al., 2006) and represent the end of the Triassic extensional period; their study is, however, beyond the scope of this work.

6. Palaeontological data and age of the formations

The scarce palaeontological data found for the Permian and Triassic rocks preserved in the Cantabrian Mountains is the main reason for the uncertainties arising in the definitions of these lithostratigraphic formations in the past and their correlations with adjacent areas. The data provided here are based on the findings of palynological, macroflora and footprints studies (Table 2). According to these data, we were able to more accurately determine the age of the identified formations

(Fig. 9), as well as discuss prior time constraints obtained without palaeontological criteria.

6.1. Palynology

The Permian and Triassic palynological record in the Cantabrian Mountains is scarce. For the Permian, only one sample recently yielded a positive result in the Sotres Formation (Fig. 9), enabling the adscription of a Kungurian age (early Permian) to this formation (Juncal et al., 2016). This association (SO1) is the only one of Permian age described to date in the Cantabrian Mountains.

Some palynological assemblages in the Triassic record have been described, although few show specimen figurations. The oldest ones were obtained in the upper Buntsandstein facies, here described as Cicera Formation, near the village of Verbios (Palentine Province, sample 1349) and Tres Mares peak (Cantabrian Province, samples 1379 and 1410) (Sánchez-Moya et al., 2005; Sopena et al., 2009). Samples 1349 and 1410 were attributed to the Ladinian (Middle Triassic), while sample 1379 was assigned to the Carnian (Late Triassic). According to an analysis of samples detected in marls and gypsum levels (Keuper

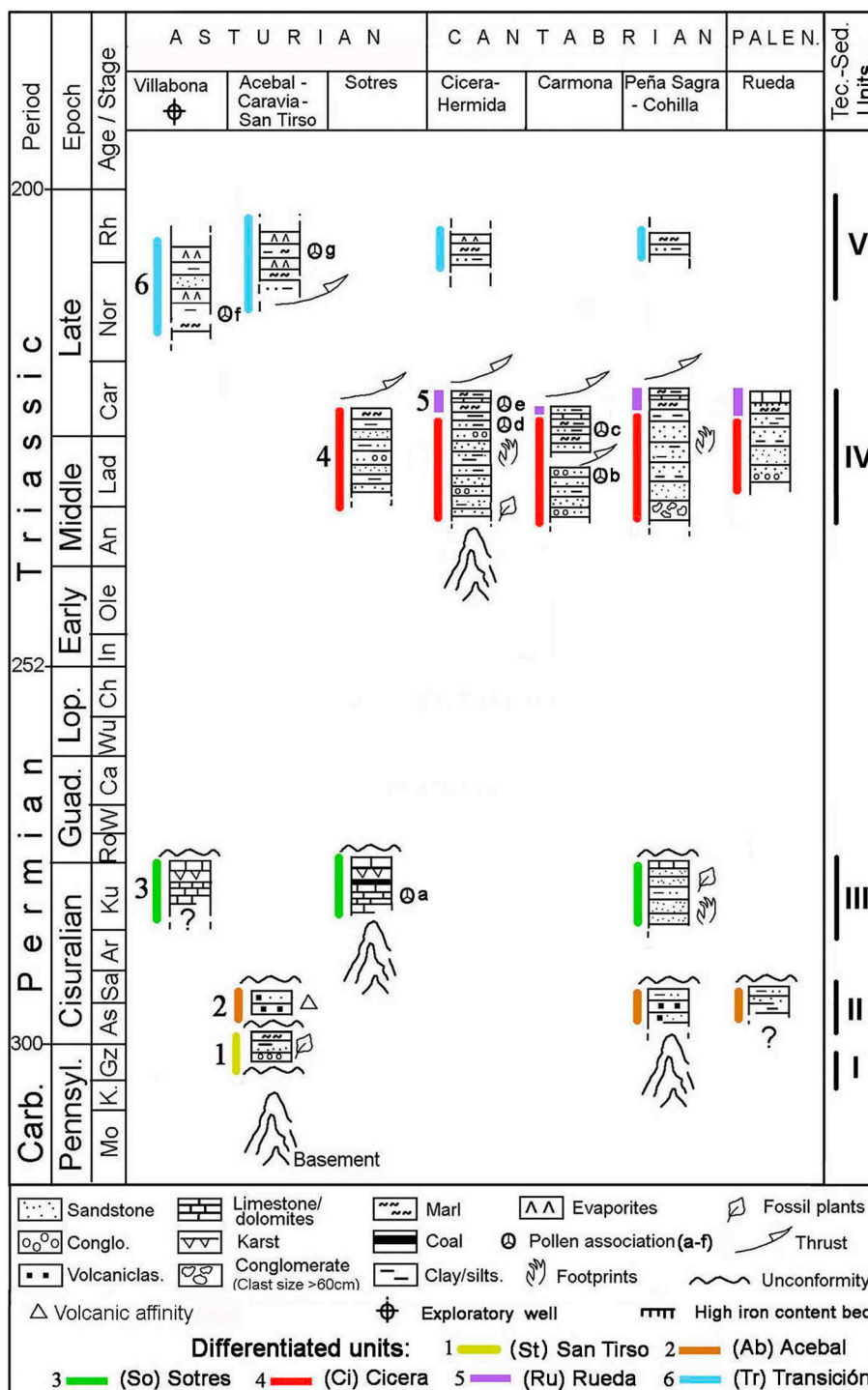


Fig. 9. Stratigraphic location of the differentiated Permian and Triassic lithostratigraphical units (1 to 6) based on new palaeontological data, and defined tectono-sedimentary units (TS I-V) in the Cantabrian Mountains. Palynological samples: a: SO1, b: Ca1, c: SP5, d: Cic11, e: Cic12, f: VBO17, g: Cu1. See Table 2 for a more detailed location of the different footprints, macroflora and pollen associations. Most of these samples are described here as the first time.

2010) propose including the “Autunian regional substage” in the Gzhelian (Late Pennsylvanian). However, recent absolute age data (Michel et al., 2015; Pellenard et al., 2017) indicate an Asselian age (early Permian; Pellenard et al., 2017) for the Autunian sedimentary record of the Autun Basin (SE France), and Sakmarian and Sakmarian/Artinskian transition ages (early Permian; Michel et al., 2015) for the Tuilières-Loiras and Viala formations in the Lodève Basin (S France) respectively.

Patac (1920) described the first Permian macroflora in the

Cantabrian Mountains near Pola de Siero (Asturian Province) including *Walchia piniformis* von Schlotheim; *Walchia hypnoides* Brongniart, *Callipteris conferta* (Stenberg) Brogniart (= *Autunia conferta* (Stenberg) Kerp), *Dicksonites* sp. and *Pecopteris* sp. Later, Wagner and Martínez-García (1982) described an early Permian macroflora near Villaviciosa comprising *Lebachia parvifolia* Florin (= *Culmitzschia parvifolia* (Florin) Kerp & Clement-Westerhof), cf. *Callipteris conferta* (Stenberg) Brongniart (= *Autunia conferta* (Stenberg) Kerp), *Taeniopteris* cf. *fallax* Goeppert and *Neuropteris neuropteroides* (Goeppert) Barthel.

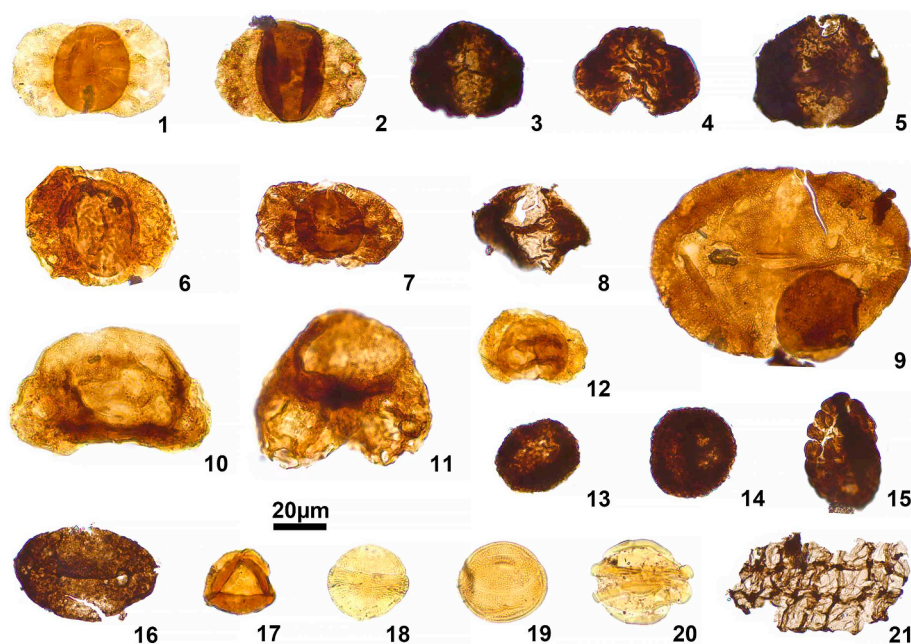


Fig. 10. Representative pollen specimens of the different associations: 1. *Triadispora crassa*, 2. *Triadispora staplinii*, 3. *Triadispora plicata*, 4. *Triadispora falcata*, 5. *Triadispora epigona*, 6. *Triadispora verrucata*, 7. *Triadispora suspecta*, 8. *Chordasporites singulichorda*, 9. *Illinites Chitonoides*, 10. *Microcachrydites fastidioides*, 11. *Microcachrydites doubingeri*, 12. *Lunatisporites noviaulensis*, 13. *Patinasporites densus*, 14. *Vallasporites ignacii*, 15. *Camerosporites secatus*, 16. *Ovalipollis pseudoalatus*, 17. *Duplicisporites granulatus*, 18. *Classopollis zwolinskae*, 19. *Classopollis torosus*, 20. *Rhaetipollis germanicus*, 21. *Plaesiodyctyon mosellanum*. See text for the locations of the specimens in the assemblages and the formations, and Fig. 4 and Table 2 for their location in the sections.

Further, Gand et al. (1997) described a fragment of *Supaia* sp. near Pico Paraes, in the Peña Sagra area (Fig. 1b). Although these beds were erroneously considered as part of the Caravia Formation by Martínez-García (1991a), data obtained from footprints allowed Gand et al. (1997) to ascribe these beds to an Artinskian - Kungurian age (early Permian). In the present study, these beds are considered part of the Sotres Formation. Moreover, we identified a new *Supaia* sp. specimen (Fig. 11) in the middle part of the Sotres Formation (Fig. 9, and sample Sagra 3 in Table 2), in the same section and probably equivalent beds to the ones described by Gand et al. (1997).

Finally, Wagner and Martínez-García (1982), Martínez-García (1991) and Wagner and Álvarez-Vázquez (2010) described a fossil flora in the lower part of the San Tirso Formation (Fig. 9) constituted, among others, of *Neuropteris* cf. *neuropteroides* (Göppert) Zeiller, *Neuropteris pseudoblissii* Potonié, *Linopteris gangamopteroides* (de Stefani) Wagner, *Callipteridium gigas* (von Gutbier) Weiss, cf. *Pseudomariopteris polymorpha* (Zeiller) Danzé-Corsin, cf. *Polymorphopteris polymorpha* (Brongniart) Wagner, *Calamites* sp. This flora is considered to indicate a “Stephanian C or lower Autunian” age.

6.3. Footprints

Permian vertebrate footprints were first described in detail in the Cantabrian Mountains by Gand et al. (1997) in Pico Paraes, near Peña Sagra (Fig. 1b), where these authors described the presence of *Hylodichnus major* and *Limnopus* in the middle part of what is here designated the Sotres Formation. This unit, as discussed above, has been erroneously correlated with the Caravia Formation (Martínez-García, 1991a). The age ascribed to this formation has changed several times (Wagner and Martínez-García, 1982; Martínez-García, 1991a, 1991b; Martínez-García et al., 1991a; Mamet and Martínez-García, 1995; Martínez-García et al., 2001, among others). In the present work, the footprints described by Gand et al. (1997) are considered as belonging to the lower-middle part of the Sotres Formation. Based on the occurrence of *Supaia* and *Hylodichnus major* in nearby beds, Gand et al. (1997) interpreted those beds as Artinskian, or even Kungurian. Here, we also note the presence of *Varanopus* cf. *rigidus* (Gand, 1987) (Fig. 12 A, and sample Sagra 2 in Table 2), in lateral equivalent beds of the neighbouring Peña Sagra section (Fig. 9). This latter track can be linked to quadrupedal, digitigrad Capthorhinidae trackmakers. Similar tracks have been observed in St-Affrique, Lodève and Le Luc, in Provence, SE

France, and recently attributed an Artinskian to Capitanian age by Laurent et al. (2015).

Demathieu and Saiz De Omeñaca (1990) described a Triassic foot-hand pair of *Rhynchosauroides* in northern Peña Sagra, without providing a clear geographic location. These rocks are both clearly within the Cicera Formation and geographically close to the described Carmona section. In the Cicera section of this same formation, we present two other footprints (Figs. 4, 9) that could correspond to Lagerpetidae (Fig. 12 B, and sample Cic x in Table 2). These footprints have been identified through the presence of a few bones of Ladinian age in Argentina and have been denoted *Coelurosaurichnus*, and not *Grallator*, because of significant differences between the two ichnotaxa (Gand and Demathieu, 2005). The footprints have been linked to biped animals



Fig. 11. *Supaia* sp. specimen. Base of the Sotres Formation of the Peña Sagra - La Cohilla section. See Figs. 4, 9 and 18, and Table 2 for stratigraphic locations. This is the second specimen of *Supaia* sp. described in the Cantabrian Mountains, after the specimen described in Gand et al. (1997).

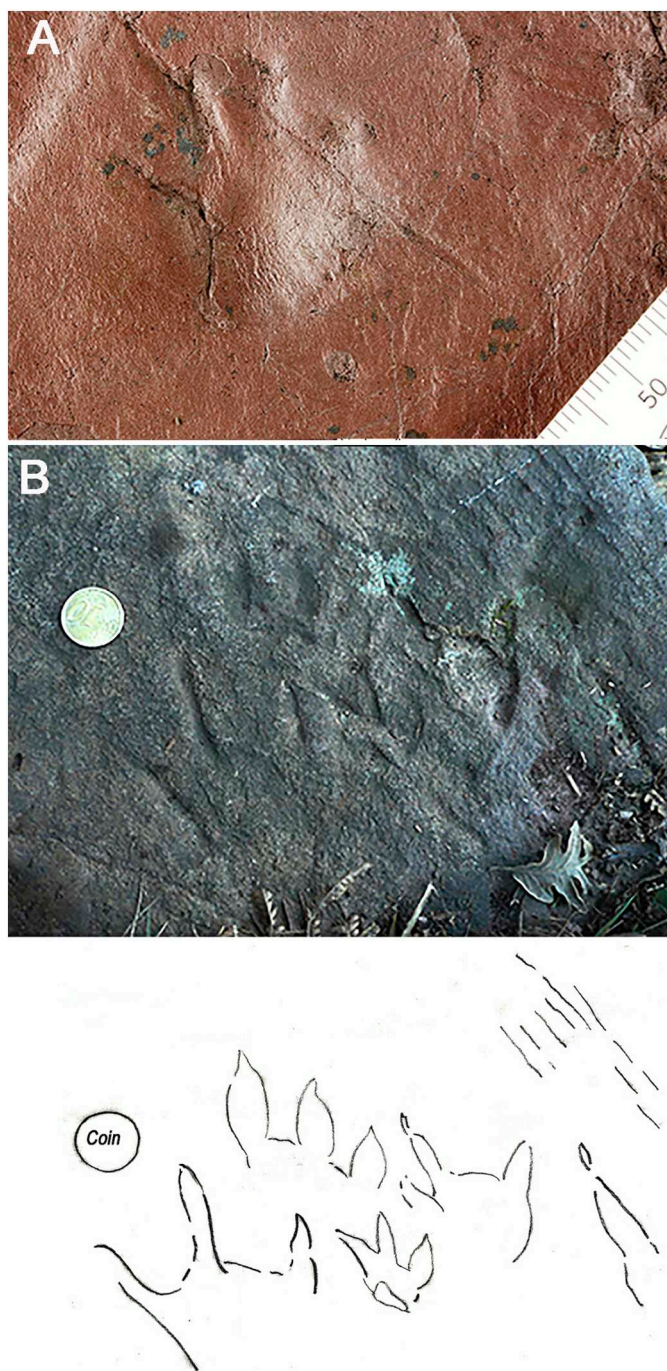


Fig. 12. A) *Varanopus rigidus*. Base of the Sotres Formation of the Peña Sagra - La Cohilla section. B) *Coelurosaurichnus*. Upper part of the Cicera Formation in the Cicera section. See Figs. 4, 9 18, and Table 2 for stratigraphic locations. Both footprints were obtained in fine sandstone beds.

according to their functional tridactyl II-IV pes, similar to numerous tridactyl footprints of dinosauriform forms found in Anisian-Ladinian beds in SE France (Gand and Demathieu, 2005).

7. Permian volcanism

The Permian volcanism of this sector is well-represented in the Acebal area (Fig. 4). Outcrops show a wide range of volcanoclastic rocks interbedded in the Permian sedimentary series.

Two types of volcanoclastic deposits are exposed: pyroclastic surge and ash fallout deposits. Pyroclastic surge deposits include levels of

coarse tuff and tuffaceous sandstone ranging in thickness from 5 cm to 5 m (Fig. 13A). In general, the whole series is characterized by coarse bedding with normal grading of pyroclast sizes. Individual levels have internal laminations or show alignments of pyroclasts. These are sub-angular, equant to elongated in shape, with sizes as large as 2 mm. The deposits are medium to poorly sorted, heterogeneous with variable proportions of juvenile fragments, cognate lithic pyroclasts, crystals, clastic fragments of sedimentary origin and glass shards. No welded fragments or fiamme structures have been identified.

Juvenile fragments are vesicle-poor and glassy, ranging from 2 μ m to 2 mm. They are composed of ferromagnesian or feldspar microphenocrysts embedded in a fine-grained, hypocristalline matrix with abundant opaque minerals and glass (Fig. 13B).

Cognate, lithic fragments are partially altered porphyritic andesites. These fragments contain phenocrysts of plagioclase and minor proportions of amphibole and/or biotite. Two subtypes have been identified depending on the modal proportion and composition of the ferromagnesian phenocrysts: a) amphibole-bearing andesites with rare pyroxene (Fig. 13C), and b) biotite-bearing andesites (Fig. 13D). Both types also contain feldspar microliths, quartz and magnetite in their groundmass. Apatite and zircon occur as accessory phases. The groundmass varies from felsitic to vitrophyric and usually shows quartz- or chalcedony-filled amygdaloids.

Isolated and partially broken igneous crystals similar to those in the cognate lithic fragments are common. Glassy fragments are scarce and small. The sedimentary components are subrounded quartz and feldspar and rare mica crystals. Their proportions vary although they increase towards the top of the Acebal Formation. In addition, juvenile crystals comprise mostly feldspars, altered amphibole and/or biotite.

The Acebal Formation ends with a 5 cm-thick ash layer interbedded with sedimentary levels (Fig. 13E). This deposit shows well-defined internal lamination, contains abundant vitric shards and quartz crystals (Fig. 13F) and is interpreted as an ash fallout distal deposit.

This volcanism shows an intermediate composition (andesites to dacites) with a mineral assemblage typical of subalkaline geochemical affinities, mainly calc-alkaline (Irvine and Baragar, 1971; McBirney, 1984). Late-Variscan calc-alkaline magmatism has been reported in the Palaeozoic basement in the Pyrenees, in the Iberian Chain (Castro et al., 2002 and references therein) and in the Cantabrian Mountains (Corretge et al., 2004; Gallastegui et al., 2004 and references therein). In the Pyrenees, plutonic massifs predominate and volcanic successions with pyroclastic deposits restricted to the Central Pyrenees. These successions range widely in age from Pennsylvanian to Cisuralian (e.g. Pereira et al., 2014 and references therein), and are mainly composed of ignimbrites and rhyolites (e.g., Castro et al., 2002; Pereira et al., 2014). In contrast, the volcanism studied here shares physical and compositional features with the Permian calc-alkaline outcrops of the Iberian Chain (Lago et al., 2004a, 2004b and references therein) and with the post-orogenic magmatism which intrudes in the Variscan basement of the Cantabrian Mountains (Corretge et al., 2004; Gallastegui et al., 2004 and references therein). The age of volcanism in the Iberian Chain is mainly Sakmarian (Lago et al., 2004 a, b and references therein; Perini and Timmerman, 2008) while the postorogenic Variscan magmatism of the Cantabrian Mountains is Asselian-Sakmarian, and mainly Asselian in the eastern Astur-Galaica Region (Gallastegui et al., 2004) of our study area. Accordingly, we propose an Asselian (up to Sakmarian), tentative age for the Permian magmatism of the Acebal Formation. Specific radiometric ages will be needed to verify this hypothesis.

8. Offshore data. Permian and Triassic remnants in the central and western North Iberian continental platform (Southern Bay of Biscay)

Identification of the Permo-Triassic rift within the continental platform of the North Iberian margin offshore is a challenge due to the scarcity of direct data and the complexity and scattered outcrops of the

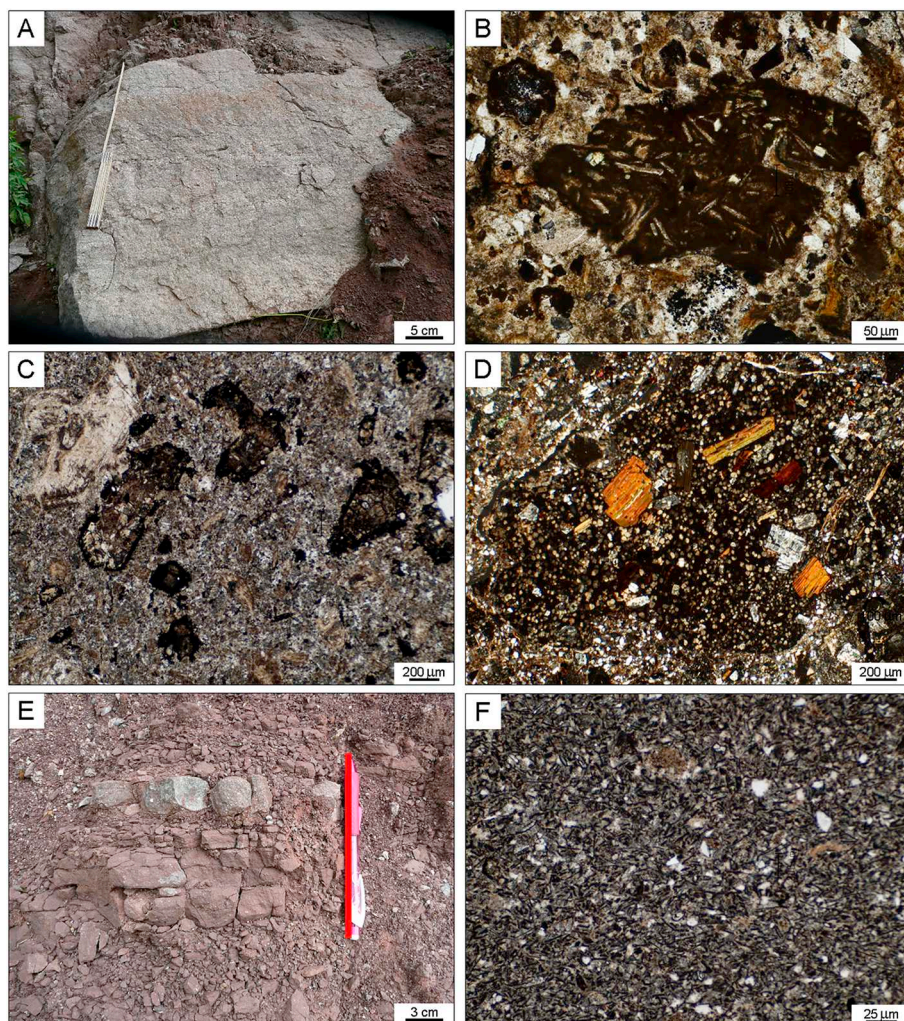


Fig. 13. A: Outcrop photograph of tuffaceous sandstones showing coarse, parallel bedding in the Acebal - P. Siero section. B: Photomicrograph (parallel polars) of a juvenile fragment of chilled margin containing feldspar microphenocrysts embedded in a fine-grained matrix with glass. C: Photomicrograph (parallel polars) of a cognate lithic fragment of amphibole andesite. D: Photomicrograph (crossed polars) of a cognate lithic fragment of biotite andesite. E: Outcrop photograph of the ash fall deposit at the top of the Acebal Formation. F: Photomicrograph (parallel polars) of the ash fall deposit, with abundant vitic shards and quartz crystal. From the base of the section, samples were obtained at: 14, 19, 58, 61, 69, 91, 113, 174, 183, 202, 219, 222, 224.5, 229 m. See also Acebal - P. Siero section in Fig. 4.

Permian and Triassic onshore (Cantabrian Mountains), which make correlations unaffordable towards offshore domains (Fig. 14). Moreover, overprinting of Permo-Triassic rifting by the subsequent Late Jurassic to Early Cretaceous rift event (e.g., Boillot et al., 1979; Derégnaucourt and Boillot, 1982; Tugend et al., 2014; Cadenas et al., 2018) limits its recognition in the central North Iberian platform, its westernmost area being the least affected (Cadenas et al., 2018). Despite these hurdles, halokynetic-related structures and diapirs emerging from the rising and squeezing of Triassic evaporites during the Mesozoic and Cenozoic tectonic events have been interpreted for the whole margin, especially within the offshore Asturian Basin (Cadenas and Fernández-Viejo, 2017; Zamora et al., 2017) and in the Parentis Basin, located in the continental platform of the southeastern Bay of Biscay (Ferrer et al., 2008; Jammes et al., 2010).

All this considered, direct offshore remnants of the Permo-Triassic rift are restricted to the Triassic deposits recovered by the Galicia-B2 and the Mar Cantábrico-K1 exploration boreholes in the western and central North Iberian continental platform, respectively (Fig. 14). Borehole Galicia-B2 was drilled by Chevron in 1977 in the exploration lead Galicia-B and borehole Mar Cantábrico-K1 was drilled by Shell in 1978 in the exploration lead Mar Cantábrico K (Borehole reports: Lanaja, 1987; Gutiérrez-Claverol and Gallastegui, 2002).

In the western North Iberian continental platform, borehole Galicia-B2 at a longitude of 6.55°W (Fig. 14), recovered, from top to bottom: 387 m of sandy mudstones and sandstones, 669 m of massive limestones with local relicts of fossil fragments, including algae, foraminifera, megafossils and lithic material, and 107 m of a red bed sequence

composed of siltstones and shales (Fig. 15A). At the measured depth, the borehole drilled uniform and massive black shales affected by low-grade Variscan metamorphism. The palaeontological report provided with the well record tentatively suggests a Lower Cretaceous age, between the Aptian and Neocomian, for the massive limestones, based on the presence of foraminifera forms such as *Pseudocyclamina* sp., *Chofatella* sp., *Trocholina* sp., *Tritaxia* sp., and algae like *Mithocodium*. The continental red beds, which do not include flora or fauna, have been ascribed to the Triassic or older age, relying on their lithological features. Finally, a Middle Ordovician to Silurian age is proposed for the lowermost dark shales, based on the presence of the *Cyathochitina* sp. chitinozoan. Seismic to well ties revealed that the borehole was drilled in the hinge of an Alpine anticline, located in the southernmost part of the continental platform (Fig. 15A). The top of the seismic basement appears at about 1 s TWT and corresponds to the Palaeozoic. In seismic profiles, the Triassic and Aptian-Neocomian series comprises an undifferentiated, parallel-layered sedimentary infill, affected by minor normal faults. Sediments are interpreted as part of the pre-hyperextension and post-hyperextension units developed prior to and after the Late Jurassic to Early Cretaceous rift event respectively (Cadenas et al., 2018).

In the central North Iberian continental platform, borehole Mar Cantábrico-K1, at longitude 5°W (Fig. 14), drilled a heterogeneous sedimentary sequence (Fig. 13B). In the uppermost part, the borehole recovered 623 m of Aptian to Barremian sandstones with interbedded limestones and claystones. These detritic deposits overlie a 405 m-thick heterogeneous unit assigned to the Neocomian. Underlying these

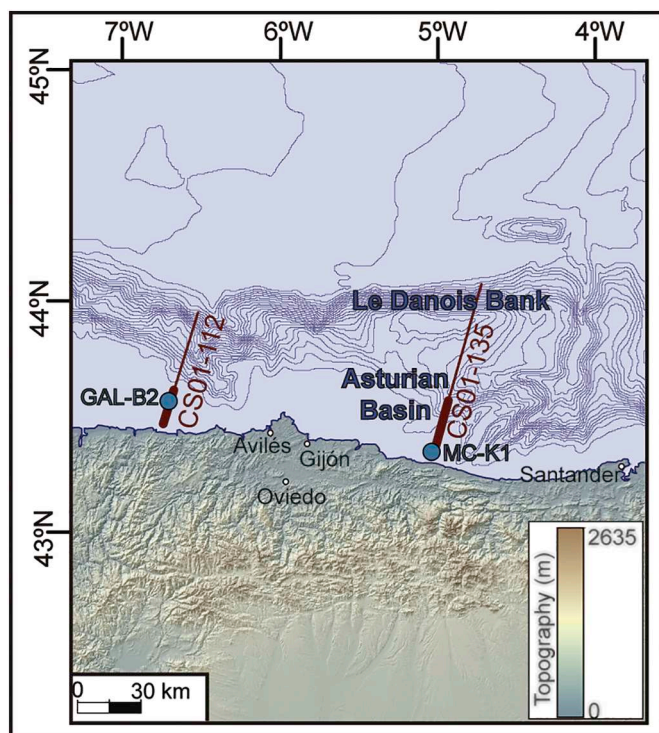


Fig. 14. Location of the Galicia-B2 (Gal-B2) and the Mar-Cantábrico K1 (MC-K1) boreholes that drilled Triassic materials and the CS01-112 and CS01-135 seismic reflection profiles, displayed in Fig. 15A, B.

Neocomian sediments, the borehole recovered 26 m of evaporites, 514 m of Valanginian to Kimmeridgian claystones, siltstones, limestones and sandstones, and 224 m of azoic red claystones harbouring siltstones and sandstones, considered equivalent to the base of the Purbeck facies. Marine Liassic limestones overlie > 600 m of Triassic deposits composed of two different lithostratigraphical units. The upper unit includes > 409 m of azoic anhydritic dolomites with claystones, considered as “Carniolas”, with an estimated age between the Raethian and Hettangian. The second unit comprises 248 m of anhydritic red claystones with sandstones and siltstones from the “Keuper facies”. This level includes some limestones interbedded at the base, ascribed to the “Muschelkalk facies”, which unconformably overlie massive Namurian limestones, and sandstones and siltstones of the Middle Carboniferous. According to the interpretation of seismic profiles, this sequence was drilled southwards of the major, south-dipping, inverted normal fault F1 (Fig. 15B). This fault limits southwards the main depocentre of the offshore Asturian Basin (Cadenas and Fernández-Viejo, 2017). Palaeozoic and Triassic sediments form the acoustic basement and are overlain by a pre-hyperextension unit including the Lower Jurassic “Liassic” limestones (Fig. 15B). This unit developed before the Late Jurassic to Early Cretaceous rift event, when the thick *syn*-hyperextension unit, corresponding to the Purbeck and Neocomian sediments, filled the Asturian Basin (Cadenas et al., 2018).

We should highlight the lack of flora and fauna within the red beds interpreted as Triassic in the two available boreholes. In the absence of time constraints, and considering the uncertainties of Permian and Triassic datings derived only from facies correlations (e.g., Wagner and Martínez-García, 1982; Martínez-García, 2004), the precise age of these units remains unclear. If we interpret these drilled red beds as Triassic, it is important to stress the lack of Permian deposits within the two stratigraphic records available offshore. Thus, in the Mar Cantábrico K1 borehole, carbonates attributed to the “Muschelkalk facies” (the Rueda Formation in this work of middle Carnian age) overlie the Palaeozoic (Carboniferous) basement, while in the borehole Galicia B2, an undifferentiated Triassic facies overlies a pre-Carboniferous Palaeozoic

basement. Most of the Triassic sediments correspond to anhydritic “Keuper facies” (upper part of the Transición Formation in this work, of Norian-Rhaetian age) which are thicker in borehole Mar-Cantábrico K1, located on the central North Iberian platform. Within this area, diapirs arising from Triassic salt horizons during subsequent tectonic events have been identified. Boillot et al. (1979) was the first to propose the occurrence of diapirs in this zone. Cadenas and Fernández-Viejo (2017) confirmed their relevance and interpreted several diapiric structures throughout the continental platform, with some diapirs particularly associated with the major, inverted, normal fault that limits the basin to the south. Cadenas (2017) defined different structural segments within the offshore Asturian Basin from west to east and a linked particular distribution of salt-related structures. Zamora et al. (2017) also differentiated eastern and western salt domains within the offshore Asturian Basin, so it is possible that some structural differences arose during the first Permian-Triassic extensional phases.

Based on the interpretation of all the available boreholes and 2D seismic reflection profiles, Cadenas et al. (2018) recently interpreted the Triassic in the western North Iberian platform as part of a pre-hyperextension unit developing prior to the Late Jurassic to Early Cretaceous rift. This basin developed on top of a thick basement belonging to a proximal domain. This implies that the basin developed mainly through stretching processes which modified the Variscan basement of western Iberia. Towards the east, in the central margin, Triassic sediments are interpreted as part of the acoustic basement within the necking domain (Cadenas et al., 2018), appearing as an area showing a crust thickness reduction of about 10 km. In this domain, sediments deposited during Permian-Triassic rifting are preserved but overprinted by the thick *syn*-hyperextension unit that developed during the Late Jurassic to Early Cretaceous rift event.

9. Tectonosedimentary evolution

The evolution of the Cantabrian Mountains during the end of the Variscan cycle and beginning of the Alpine cycle has been little studied, due to the scarce data on the age, sedimentary environment and structure of the Permian and Triassic. Based on new data from this study, we can propose a first approach to the tectonosedimentary evolution of this zone during Permian-Triassic times. This period is related to intense tectonic activity interrupted by periods of stability that could amount to tens of Ma. As a result, Permian-Triassic sedimentary refill is recorded in five tectono-sedimentary units (TSU I–V) (Fig. 9).

During the Gzhelian (uppermost Carboniferous) and probably also during the earliest Asselian (lower Permian, age of the first post-Variscan intrusions), the last structures related to the Variscan Orogeny were generated. These structures are NW-SE trending strike-slip faults with a dextral component that have traditionally been called “late Variscan” faults (Arthaud and Matte, 1975, 1977). Rodríguez-Fernández and Heredia (1987) relate the late Variscan faults with the final phases of closing of the Cantabrian Orocline (Asturian Arc), which can not continue to progress through thin-skinned tectonics. In this way the late Variscan faults must have accommodate the last Variscan shortening. In some cases, the movement of these late Variscan faults induced the reactivation of Variscan thrusts, such as the NE-SW La Peña fault or the SW-NE to E-W Liébana fault (Fig. 1b). Many syntectonic sediments linked to this final episode of the Variscan Orogeny are usually not preserved, but the San Tirso Formation (Velando et al., 1975), which is late Gzhelian - Asselian in age, can be associated with this event and here represents the unit TSU I (Fig. 9).

In the early Permian (Asselian), the Variscan belt collapsed, generating narrow and isolated basins (Fig. 16). These basins, which were controlled by reactivation of Variscan and late Variscan structures, had close source areas and remained active throughout most of the Cisuralian. As result of this activity, units TSU II and III developed (Fig. 9). Basins controlled by the reactivation of Variscan structures run in a NE-

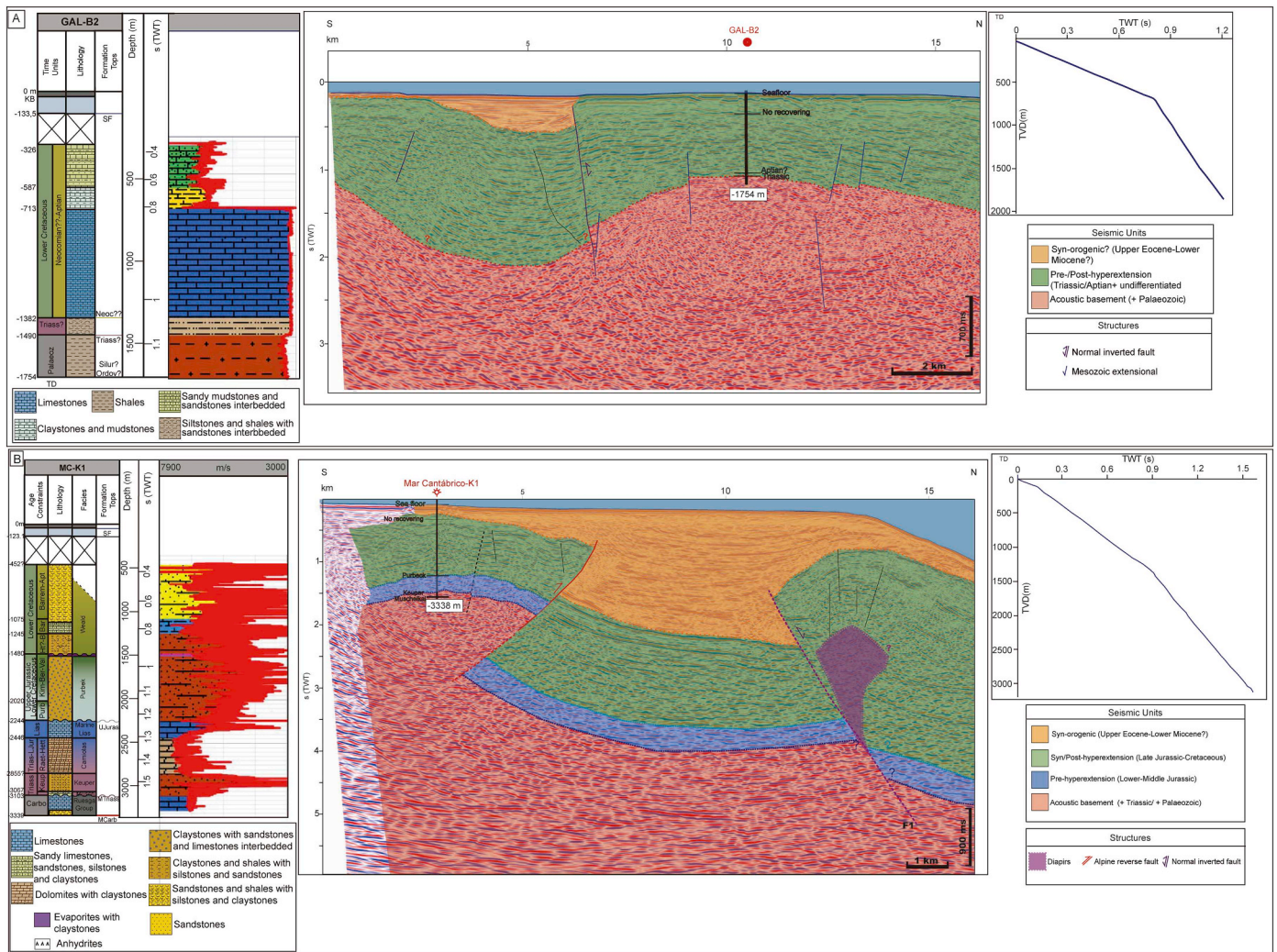


Fig. 15. A- Geological description and seismic to well ties at borehole Galicia-B2 and profile CS01-112 in the western North Iberian continental platform. The well record shows the ages of sediments, the lithologies and the main formation tops defined along the borehole. The sonic log displayed to the right was used to constrain the velocity model that enabled the development of the T-D chart shown below. We used the T-D chart to introduce borehole data in the 2D seismic reflection profile CS01-112, crossing the western North Iberian margin from south to north. The seismic line shows the interpretation of the main seismic units and structures developed during the Mesozoic extension. Exaggerated vertical scale. At the bottom, the uninterpreted seismic line is displayed on a 1:1 scale; B- Geological description and seismic to well ties at borehole Mar Cantábrico-K1 and profile CS01-135 in the central North Iberian continental platform. The well record shows the ages of sediments, the lithologies, the geological facies and the main formation tops defined along the borehole. The sonic log displayed to the right was used to constrain the velocity model that enabled the construction of the T-D chart shown below. We used the T-D chart to introduce borehole data in the 2D seismic reflection profile CS01-135, crossing the central North Iberian margin from south to north. The seismic line shows the interpretation of the main seismic units and structures developed during Mesozoic extension and Alpine compression. Exaggerated vertical scale. At the bottom, the uninterpreted seismic line is displayed on a 1:1 scale. See location of the Galicia-B2 (Gal-B2) and the Mar-Cantábrico K1 (MC-K1) boreholes and the CS01-112 and CS01-135 seismic reflection profiles in Fig. 14.

SW direction, such as the La Camocha, La Justa-Aramil and Villaviciosa basins (B, C and D in Fig. 16), to E-W, like the Sotres-La Hermida basin (E in Fig. 16). Basins associated with the reactivation of Late Variscan structures trend in a NW-SE direction, such as the Villabona, Cueto Turis, Peña Sagra and Peña Labra basins (A, F, G and H, respectively, in Fig. 16). The extensional regime generated a calc-alkaline magmatism that produced volcanic rocks (Acebal Formation, TSU II) interbedded in the sedimentary Permian sequences (Suárez-Rodríguez, 1988; Valverde-Vaquero, 1992) and a large number of small plutonic intruded bodies of Asselian age in close proximity to late Variscan faults (Gallastegui et al., 1990) (Fig. 16). In relation to the early Permian extension, a subhorizontal cleavage cutting the Variscan structures developed, especially in the Carboniferous rocks (mainly slates) of the Pisuerga Carrión Region (Aller et al., 2004).

Extensional activity resumed in the Middle Triassic (Ladinian), which means that during > 30 Myr there were no deposits in the study

area. This gave rise to deep karstification of Palaeozoic limestones (well-developed in the Picos de Europa area) and of the lacustrine carbonates representing the last Permian deposits (Sotres Formation; Figs. 6B, 9), prior to deposition of the Middle Triassic rocks. At this time, related basins are more extensive, as shown by the Cicera Formation (TSU IV) (Fig. 9) with its far away source areas (Sánchez-Martínez et al., 2012) and thicker sedimentary infill (Fig. 17). In the study area, two basins developed, although isolated in time and space: the Corrales-Aguilar sub-basin in the SE (B in Fig. 17), active from the Middle Triassic (late Anisian), and the Gijón-Villaviciosa sub-basin in the NW (A in Fig. 17), active only during the Late Triassic (Norian-Rhaetian) and represented by the Transición Formation (TSU V) (Fig. 9). These basins were separated by a horst (Cuera high) in which there was no sedimentation in Permo-Triassic times (Fig. 17). In this area, the latest Lower Cretaceous sediments (Aptian) overlie Palaeozoic rocks (Martínez-García, 1980; Navarro, 1984). Both the Corrales-

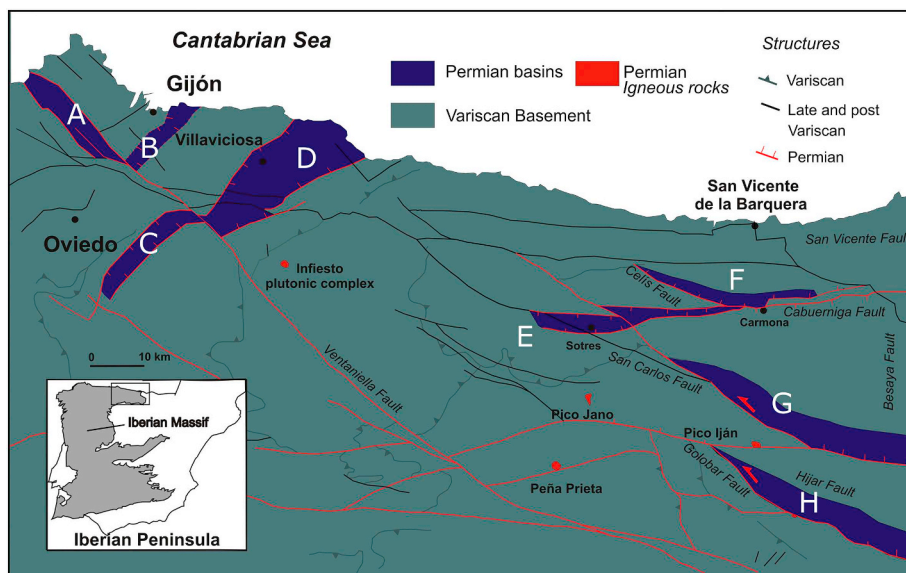


Fig. 16. Geological sketch showing the location of the main Permian basins, igneous rocks and faults in the central Cantabrian Mountains. Permian basins: A) Villabona, B) La Camocha, C) La Justa-Aramil, D) Villaviciosa, E) Sotres-La Hermida, F) Cueto Turis, G) Peña Sagra, H) Peña Labra. The Mesozoic cover in the western Vasco-Cantábrica Region has been deleted to show the relationships between Permian basins and Variscan structures in the whole study area. Variscan faults that were reactivated in Permian times are shown in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Aguilar and Gijón-Villaviciosa sub-basins seem limited to the SW by the Ventaniella fault, although some Triassic deposits were found offshore in the borehole GAL-B2 (Fig. 15), to the west of the trace of the Ventaniella fault.

The Gijón-Villaviciosa sub-basin was quite symmetrical during the early Triassic, while the Corrales-Aguilar sub-basin had its depocentre displaced towards its easternmost zone. During the Middle and Late Triassic, the southern Corrales-Aguilar sub-basin corresponds to a semigraben (García-Espina, 1997) related to the Ventaniella fault (Fig. 17), which extends to the N until the Cuera fault (Figs. 1b, 17). However, the basin had a depocentre in the eastern middle part of this semigraben, a symmetrical sub-graben formed between the Pantrieme and Cuerres faults (García-Espina, 1997) and bounded to the E by the San Carlos fault (Fig. 17). This sub-graben displays the maximum thickness of the Middle-Late Triassic lithostratigraphic units (Fig. 4). The San Carlos and San Vicente-Besaya faults delimit areas with different number and geometry of normal faults, so they can be interpreted as extensional transfer faults, produced by the reactivation of NW-SE late Variscan structures. During the Late Triassic, the basin was strongly compartmentalized, showing several depocenters related to different normal faults. To the east of the San Vicente-Besaya fault, the

thickness of the Late Triassic evaporite deposits increases, allowing for the development of diapirism, which is generally scarce in the Corrales-Aguilar sub-basin. Evaporites are absent in the onshore Gijón-Villaviciosa sub-basin (Fig. 17), although these have been described in its offshore continuation to the east (Fig. 15).

Offshore, Triassic sediments are preserved in the southernmost area of the continental platform. Triassic units correspond mainly to anhydritic Keuper facies (Transición Formation), which are thicker in borehole Mar-Cantábrico K1, in the central North Iberian platform, where diapirs arising from Triassic evaporates through zones of tectonic weakness lineaments are quite frequent in some areas (CS01-135, Fig. 15). In the western continental platform, the early phases of development of the NW-SE basin identified can be ascribed to the Triassic (Cadenas et al., 2018) according to the Triassic sediments recovered by borehole Galicia-B2 southwards. However, the lack of data precludes further interpretations of the relevance of Triassic events in shaping the offshore Asturian Basin (Fig. 15).

10. Discussion

Through geological mapping and sedimentological and petrological

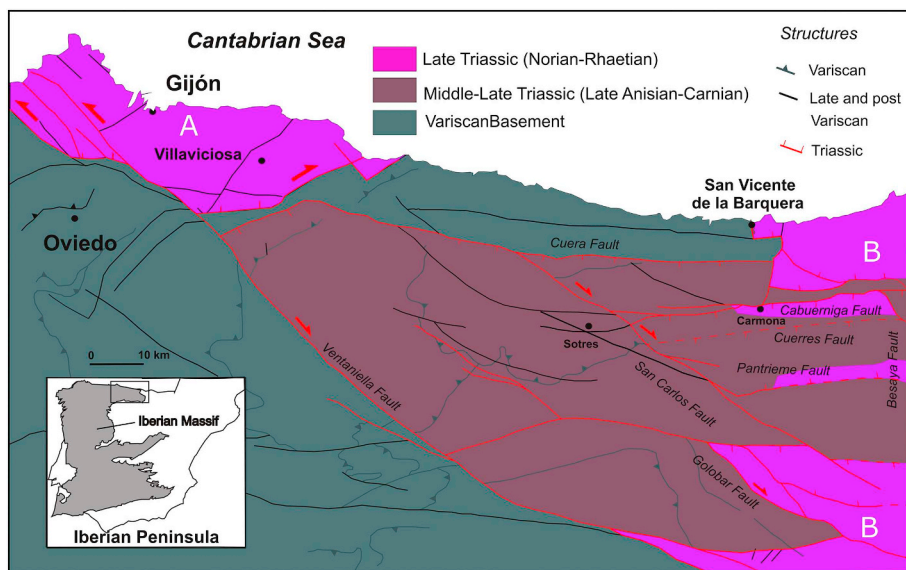


Fig. 17. Geological sketch showing the location of the main Triassic faults and sub-basins of the western Basque-Cantabrian basin in the central Cantabrian Mountains. Triassic sub-basins: A) Gijón-Villaviciosa, B) Corrales-Aguilar. Variscan faults that were reactivated in Triassic times are shown in red. See Fig. 16 to compare the change of basin configurations from the Permian to Triassic. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

studies we have been able to characterize the lithostratigraphical formations described here. Further, for the first time, new palaeontological data serve to assign a direct age to all formations except the Acebal (volcanic) Formation. However, as discussed above, an Asselian-Sakmarian age is estimated for this formation based on the composition of its magmatism, and also considering its stratigraphic position, in between units of well-established age (Fig. 18).

Our multidisciplinary approach has made it possible to identify a late-Variscan tectosedimentary phase (latest Carboniferous-earliest Permian), other post-Variscan phases (lower Permian extension) and one last phase at the beginning of the Alpine cycle (Middle-Late Triassic extension). The Permian extensional event is related to the collapse of the Variscan orogeny, whereas the Triassic event is related to rifting (Pangea break-up). There is a gap of 30 Myr between these two events. It is worth noting that previous works have usually evoked a single extensional Permian-Triassic rifting event.

This new stratigraphic arrangement provides insight into the lithostratigraphical units established to date. Thus, some units have been ruled out as they have been defined differently in the sedimentary record and with different ages. The latter is the case of the San Tirso Formation (Figs. 1b, 4); our new geological mapping separates this formation from the overlying Acebal Formation, whose base is Asselian. Moreover, the location of fossil floras (Wagner and Martínez-García, 1982) near its base, serves to assign to this formation a “Stephanian C age”, although its upper portion could reach the Asselian. This age, together with its basal unconformity, the scarcity of Variscan deformation and its continental character, make the San Tirso Formation an exception in the Variscan succession of the Cantabrian Mountains, which can be related to the Late Variscan deformations.

The Caravia Formation (Fig. 18), has been considered early Permian, middle Permian and even late Permian in age without palaeontological data (Martínez-García, 1991a, 1991b; Martínez-García et al., 2001). Our palaeontological criteria indicates that this Formation has a Middle Triassic age. We name it as the Cicera Formation. Other units showing local development, such as the Sagra Formation, were initially well defined (Gand et al., 1997) but subsequently wrongly correlated with the Caravia Formation (Martínez-García, 1991a). Similarly, the Sotres Formation was first ascribed an “Autunian age” and considered of marine origin with volcanic rocks at the base (Martínez-García, 1991a). However, this formation includes carbonates that are clearly of continental origin (Mamet and Martínez-García, 1995). Palaeontological data assign a Kungurian age to this formation (Juncal et al., 2016) and the volcanic rocks described at its base (Martínez-García, 1991a) would be part of what is defined in this study as the Acebal Formation (Fig. 18).

The Rueda Formation is also firstly described in the present work. The stratigraphic location of this formation, its limited thickness, its marine origin and estimated middle Carnian age are of great relevance from a palaeogeographic point of view. It is not a clear temporal equivalent to other Middle Triassic (“Muschelkalk facies platforms”) or Late Triassic (“Keuper facies”) sedimentary successions described in the rest of the Iberian domain (Escudero-Mozo et al., 2015). Further, the sedimentary record of the unit referred to in this work as Cicera Formation, of Ladinian-Carnian age, has been also considered part of the “Buntsandstein” units (García-Mondejar et al., 1986; Martínez-García, 1991a). However, equivalent units have been assigned an Olenekian-Anisian age in the rest of Iberia (López-Gómez et al., 2002). A possible interpretation is that the Triassic sedimentary record is younger in the Basque-Cantabrian Basin than in neighbouring basins of the Iberia domain, which would confirm the large gap in sedimentation, probably from the Kungurian or early Roadian (late early Permian-early middle Permian) to the late Anisian or Ladinian (Middle Triassic). It follows that the sedimentation gap could have lasted > 30 Myr. In the study zone, this interruption in sedimentation started at the end of the Sotres Formation deposition and is recorded by a karst surface in all the studied sections (Figs. 6B, 8i), even in the Villabona borehole (Fig. 5). In

addition, the lateral extension of this surface points to its considerable palaeogeographic significance, and likely represents the subaerial exposure of a lake or lakes that occupied most of the Permian Cantabrian basins at the end of the Cisuralian (early Permian).

The vertical succession of the sedimentary record presented in this contribution, its interruptions and its subdivision into five TS units allow us to compare the Permian and Triassic record in the Cantabrian

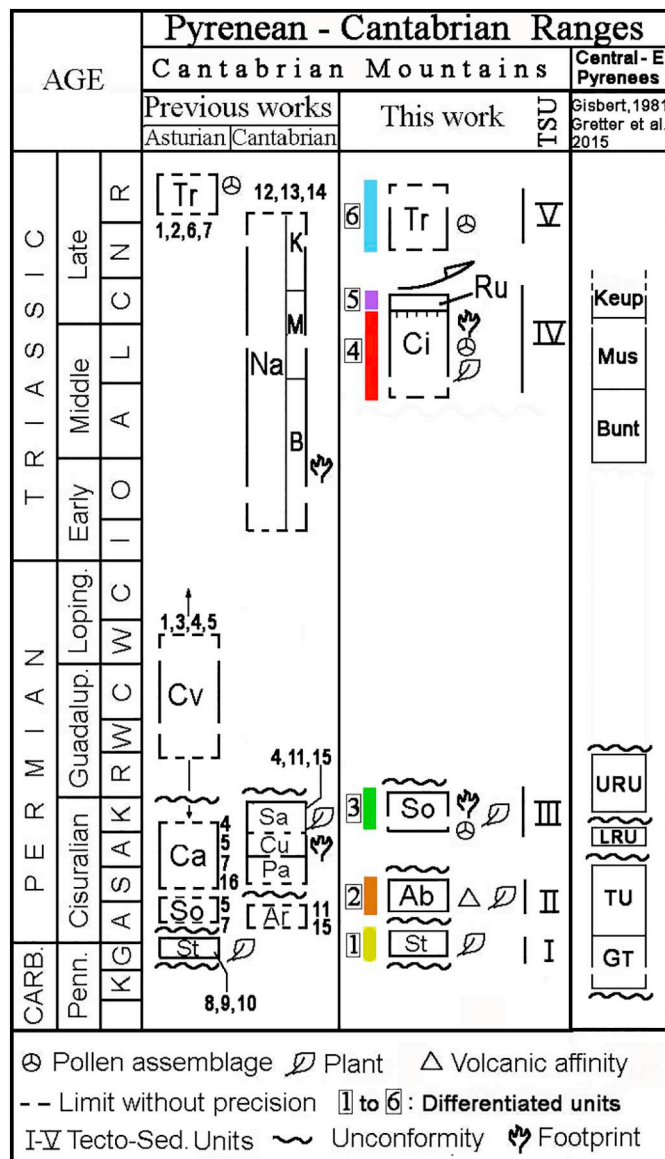


Fig. 18. Comparison between our proposed post-Variscan Permian-Triassic stratigraphy and those derived from previous works in the Cantabrian Mountains (left), and comparison of the differentiated lithostratigraphical and tectono-sedimentary units of the Cantabrian Mountains with those of the Central and E Pyrenees (right). Numbers represent references with supporting data: 1- Martínez-García et al. (1998); 2- Suárez-Vega (1974); 3- Martínez-García (1981); 4- Martínez-García (1991a); 5- Martínez-García (1991b); 6- De la Horra et al. (2012); 7- Manjón and Gutiérrez-Claverol (1991); 8- Martínez-García, 1991a, 1991b; 9- Martínez-García et al. (2001); 10- Wagner and Martínez-García (1982); 11- Gand et al. (1997); 12- Maas (1974); 13- García-Mondejar et al. (1986); 14- Robles and Pujalte (2004); 15- Robles (2004); 16- Martínez-García (2004). Units: St- San Tirso; So- Sotres; Ca- Cabranes; Cv- Caravia; Tr- Tránsito; Ar- Arroyo; Pa- Paraes; Cu- La Cuesta; Na- Nansa; B- Buntsandstein; M- Muschelkalk; K- Keuper; Ab- Acebal; Ci- Cicera; GU- Gray Unit; TU- Transit Unit; LRU- Lower Red Sandstone; URS- Upper Red Sandstone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Mountains with other basins of the central and eastern Pyrenees (Fig. 1a) described by Gisbert (1981) and Gretter et al. (2015) of the lithostratigraphical succession in these latter basins, a possible lateral comparison could be done with the Cantabrian Mountains succession (Fig. 18). The San Tirso and Acebal units, or TSI and TSII, would be broadly time-equivalent to the Gray and Transition units of the central and eastern Pyrenees. On the other hand, the late Kungurian-early Roadian sedimentary interruption at the top of the lacustrine deposits of the Sotres Formation could broadly correspond to an interruption of similar age, represented by the top of the Upper Red Unit in the central and eastern Pyrenean basins. In the same way, the period without sedimentation and/or erosion spanned from the uppermost Kungurian-lowermost Roadian (related to the top of the Sotres Formation) to the late Anisian (Middle Triassic) in the western Basque-Cantabrian Basin and could correspond to the interruption in sedimentation lasting until the Spathian (late Early Triassic) in the central and the eastern Pyrenean basins (Mujal et al., 2016). This lateral comparison of the main TS sequences between both areas is highly relevant. It confirms a broadly similar post-Variscan evolution both for all the basins of northern Iberia, and for basins developing in the western Tethys realm, presently in SE France and Sardinia. The main Permian-Triassic tectono-sedimentary units of these basins were indeed recently compared to the units identified in the basins of the central and eastern Pyrenees by Gretter et al. (2015).

11. Conclusions

The Cantabrian Mountains and Pyrenees represent the western and eastern ranges, respectively, of the Pyrenean-Cantabrian Orogen that resulted from the collision of the Iberian and Eurasian plates, mostly in Cenozoic times. Despite their coetaneous origin, with neighbouring basins, the tectono-sedimentary evolution of the Cantabrian Mountains at the beginning of the Alpine cycle (extensional phases) has so far been considered independently. A specific geodynamic evolution has been interpreted different to the other western Peri-Tethys realm basins, including the eastern part of the some orogen, corresponding to the Pyrenees. This has generated erroneous palaeogeographic considerations in all these domains from the latest Carboniferous to the Late Triassic.

Our multidisciplinary study was based on detailed geological mapping, field sections, stratigraphy, sedimentology and volcanic rock petrology along with new palaeontological data (pollen associations, macroflora and footprints). This combined approach has served to differentiate five new tectono-sedimentary units (TS I – TS V) interrupted by periods of tectonic stability. As a result, we define a new lithostratigraphical succession consisting of six formations: San Tirso, Acebal, Sotres, Cicera and Transición formations. This new stratigraphic model simplifies the nomenclature of previous studies and avoids definitions of stratigraphic units resulting from poorly defined ages or repetitions. Our study was enhanced with offshore data obtained from two boreholes and 2D reflection seismic profiles acquired in the North Iberian continental platform, and with onshore data from the Villabona Mine borehole. The main characteristics of the five differentiated tectono-sedimentary units are:

TS I. During the latest Carboniferous and earliest Permian (late Gzhelian-early Asselian), late-Variscan dextral strike-slip faults developed, accommodating the latest compressional orogenic efforts. Related to this late-Variscan event, small and isolated basins were generated and hosted the San Tirso Formation record, which consists of medium to distal humid alluvial fan sediments.

TS II. The Variscan orogen collapsed in early Permian times, and narrow isolated basins developed controlled by the reactivation of the E-W and NE-SW Variscan structures and NW-SE late Variscan structures. Associated with the Permian extensional collapse (Asselian-Sakmarian), a calc-alkaline magmatism represented by volcanic and volcanosedimentary intercalations (Acebal Formation) appeared in the

Permian basins, together with small plutons in the Variscan basement. Subhorizontal cleavages developed during this Permian extensional event.

TS III. At the end of the early Permian (Kungurian), further reactivation of Variscan and late Variscan structures led to alluvial and carbonate lacustrine sedimentation (Sotres Formation), representing the end of Permian sedimentation in the Basque-Cantabrian Basin. This interruption in sedimentation gave way to a deep karstification process that has been acknowledged in the whole basin.

TS IV. After about 30 Myr of interruption, sedimentation recommenced during a rifting event of Middle-Late Triassic age (late Anisian-middle Carnian). During this event, a large, compartmentalized extensional basin was generated. A thick fluvial sedimentary record (Cicera Formation or “Buntsandstein”) filled this basin. This sedimentation accumulated in the Corrales-Aguilar sub-basin in the SE, and ended with the first Mesozoic short, carbonate marine incursion (Rueda Formation) or “Muschelkalk”. In this new stratigraphic succession, the so-called “Buntsandstein” and “Muschelkalk” units are remarkably younger than in the rest of Iberia.

TS V. The younger Triassic (Norian-Rhaetian) sedimentary record built up both in the Corrales-Aguilar sub-basin and the Gijón-Villaviciosa sub-basin to the NW. This record is represented by shallow marine carbonate sediments (Transición Formation). During the Late Triassic, the basins were much more compartmentalized and developed several depocenters related to different normal faults.

Main lithostratigraphical differences between the Asturian, Palentine and Cantabrian areas of the Cantabrian Basin are recorded laterally by the presence or absence of some units. This is linked to the development of a significant palaeorelief and to tectonic activity.

The more precise I–V TS units defined here, including the volcanism character of TS II, enable a broad lateral comparison of these units with the TS units defined in the central and eastern Pyrenees. This suggests a similar post-Variscan tectono-sedimentary evolution (with slight time differences) for all the Pyrenean-Cantabrian basins, from the eastern Pyrenean basins to the western Basque-Cantabrian basin.

12. Short conclusion

The beginning of the Alpine cycle in the Cantabrian Mountains has been previously interpreted within a specific geodynamic context, independently from the general tectono-sedimentary phases of neighbouring western Peri-Tethys basins of the same age. Based on detailed multidisciplinary field work, including one onshore borehole, 2D reflection seismic profiles and new age data, we have defined six new lithostratigraphical units and five new tectono-sedimentary units (TS I–V). For the first time, we propose a general, unifying model for the post-Variscan to early Alpine tectono-sedimentary evolution of the whole Pyrenean-Cantabrian. This novel interpretation will simplify palaeogeographic interpretations of the Permian-Triassic evolution of the Pyrenean belt.

Acknowledgements

This work was funded by projects CGL2014-52699P and CGL2015-70970-P (Spanish Ministry of Economy and Competitiveness and FEDER Funds of the European Union), as well as projects: “Sistemas Sedimentarios y Variabilidad Climática” (642853) of the CSIC, Basin Analysis (910429), and Palaeoclimatology and Global Change (910198) of the Universidad Complutense de Madrid. The authors thank Luis Villa Iglesias and José Antonio Marín Barcaítegui (MINERSA GROUP) for providing all the required borehole data from the Villabona Mine (Asturias) and for facilitating access to the mines for sampling. We thank both anonymous referees and Editor Andre Strasser for improving the final version with their comments, and A. Burton for reviewing the English.

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