Accepted Manuscript

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, Fidel Martín-González, Nemesio Heredia, Raúl de la Horra, José F. Barrenechea, Patricia Cadenas, Manuel Juncal, José B. Diez, Violeta Borruel-Abadía, David Pedreira, Joaquín García-Sansegundo, Pedro Farias, Carlos Galé, Marceliano Lago, Teresa Ubide, Gabriela Fernández-Viejo, Georges Gand

PII: S0012-8252(18)30425-2
DOI: https://doi.org/10.1016/j.earscirev.2018.11.008
Reference: EARTH 2731

To appear in: *Earth-Science Reviews*

Received date: 17 July 2018
Revised date: 13 November 2018
Accepted date: 13 November 2018

Please cite this article as: José López-Gómez, Fidel Martín-González, Nemesio Heredia, Raúl de la Horra, José F. Barrenechea, Patricia Cadenas, Manuel Juncal, José B. Diez, Violeta Borruel-Abadía, David Pedreira, Joaquín García-Sansegundo, Pedro Farias, Carlos Galé, Marceliano Lago, Teresa Ubide, Gabriela Fernández-Viejo, Georges Gand , 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. Earth (2018), https://doi.org/10.1016/j.earscirev.2018.11.008

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,*] jlopez@ucm.es, Fidel Martín-González[b] fidel.martin@urjc.es, Nemesio Heredia[c] n.heredia@igme.es, Raúl de la Horra[d] rhorraba@ucm.es, José F. Barrenechea[a,e] barrenechea@ucm.es, Patricia Cadenas[f] pcadenas@geol.uniovi.es, Manuel Juncal[g] majuncales@uvigo.es, José B. Diez[g] jbdiez@uvigo.es, Violeta Borruel-Abadía[a,h] violeta.borruel@igeo.ucm-csic.es, David Pedreira[c] david@geol.uniovi.es, Joaquín García-Sansegundo[c] jgsansegundo@geol.uniovi.es, Pedro Farias[c] pfarias@geol.uniovi.es, Carlos Galé[i] carlos.gale@gmail.com, Marceliano Lago[i] mlago@unizar.es, Teresa Ubide[j] t.ubide@uq.edu.au, Gabriela Fernández-Viejo[f] gaby@geol.uniovi.es, Georges Gand[k] georgesb.gand@orange.fr

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

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

[c]Instituto Geologico 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

[*]Corresponding author.

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.

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 reactivation 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.

Keywords: Cantabrian Mountains, Pyrenees, Pyrenean-Cantabrian Orogen, Alpine Cycle, Permian-Triassic, post-Variscan tectonics

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., 1996; Gallastegui et al., 2002; Barnolas and Pujalte, 2004; Pedreira et al., 2007; Martín-González and Heredia, 2011 a, b) (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 palaeogeographical 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 De Jong (1971), Martínez-García (1981), García-Mondejar et al. (1986), Suárez-Rodríguez (1988). More recently, numerous synthesis studies have been carried out by Martínez-García (1991, 1999), 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), Sopeña et al. (2009) and Juncal et al. (2016). This scarcity of data led to investigations of tectono-sedimentary relationships in the past century (Julivert, 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, b; 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 are 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 2,600 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 extensión of the Basque-Cantabrian Basin, since both are united 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 compartmentalised, broken foreland basin (Martin-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., 2012 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). 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, b; 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).

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 Palentian 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, 2007; 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, b; 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, b) 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. 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 Ríocorvo 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:

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 (Martinez-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 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.

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 volcaniclastic 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.

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, b), 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 volcaniclastics beds, thin coal seam layers, and up to 90 m thickness of alternating grey 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 to 34 m in the Sotres area. In other sections (e.g., Peña Sagra-Cohilla section, Fig. 1b) this formation is composed of medium- to coarse-grained sandstones in its lower part, and carbonate beds towards the top, where a large karst surface frequently develops (Fig. 6b).

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, b; Martínez-García et al., 1991; 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).

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 grey 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.

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., Dubar el al., 1963; 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 figure 4), we propose a variable thickness of 320 to 610 m. The unit rapidly loses thickness and 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, volcaniclastic 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 volcaniclastic origin, 2 of shallow marine origin and 1 of sabkha origin. Figure 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 figure 4 while some of the main representative elements observed in the field can be seen in figure 8. We describe the architectural elements identified in each of the stratigraphic units defined as fallow:

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).

Acebal Formation: This formation includes elements Vt, Vc, Ve, Vf, Fl, Ls, Fm, Stp2 and GStp. Essentially, the formation consists of different types of volcaniclastic deposits accumulated during successive pulses (Fig. 8 j, k, l), similar to examples described by Lago et al. (2004a, b) 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 palaeosoils 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.

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, b; Martínez-García et al., 1991) but later considered to be continental in origin due to the presence of sponge-bacterial bafflestones harbouring

Bevocastria 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.

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 Gullifort 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 *Plaesiodictyon 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, 2014) 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. (2012).

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. (2017) on the island of Mallorca. The formation constitutes the first Mesozoic marine ingression 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.

Transición Formation: This formation is basically represented by the element Sbk. Its lithology and thickness may change depending on the area. In the 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; Sopeña 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 facies) in Aguilar de Campoo (Palentine Province), which are probably time-equivalent to the above mentioned Transición Formation, we assign a Norian age (Late Triassic) to these facies, as suggested by Salvany (1990a, b). Later Calvet et al. (1993) obtained an early-middle Norian age for a pollen sample from a similar facies near Reinosa (Cantabrian Province). Also in similar facies, Barrón et al. (2001) assigned a late Carnian to early Norian age to laminated gypsum samples near Poza de la Sal (Cantabria Province).

In the Transición Formation, near Huerces (Asturian Province), Martínez-García et al. (1998) obtained a late Rhaetian age for one analysed sample. In this same unit, Barrón et al. (2002, 2005, 2006) described a Rhaetian age based on several different samples.

We obtained six positive pollen samples in the studied formations (Fig. 9): San Pedro 5 (SP5), Carmona 1 (Ca1), Cic11, Cic12, VBO17 and Cueli 1 (Cu1). The oldest Triassic palynological assemblages were from the Cicera Formation in the Carmona section (Fig. 9, Table 2): samples SP5 and Ca1. These two samples show very similar associations represented by *Camerosporites secatus* Leschik 1956, *Chordasporites singulichorda* Klaus 1960, *Duplicisporites granulatus* (Leschik) Scheuring 1970, *Illinites chitonoides* Klaus 1964, *Lunatisporites noviaulensis* (Leschik) Jersey 1979, *Microcachryidites doubingeri* Klaus 1964, *Microcachryidites fastidioides* (Jansonius) Klaus 1964, *Ovalipollis pseudoalatus* (Thiergart) Schuurman 1976, *Triadispora crassa* Klaus 1964, *Triadispora falcata* Klaus 1964, *Triadispora plicata* Klaus 1964, *Triadispora staplinii* (Jansonius) Klaus 1964, *Triadispora suspecta* Klaus 1964 and *Triadispora verrucata* (Schulz) Scheuring 1970. (Fig. 10, numbers 1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 15, 16, 17). The presence of typical Middle Triassic taxa as *Lunatisporites noviaulensis*, *Illinites chitonoides*, *Microcachryidites doubingeri*, and *Michrocachryidites fastidioides*, together with circumpollen species, that diversified during late Ladinian (e.g. Kürschner and Herngreen, 2010; Juncal et al., 2018), all indicate a Longobardian age (late Ladinian).

Samples Cic11 and Cic12 were obtained near the sample collected from the Cicera Formation, in the Cicera Section (Fig. 9, Table 2). They are represented by *Camerosporites secatus* Leschik 1956, *Duplicisporites granulatus* (Leschik) Scheuring 1970, *Chordasporites singulichorda* Klaus 1960, *Ovalipollis pseudoalatus* (Thiergart) Schuurman 1976, *Patinasporites densus* Leschik 1955, *Triadispora crassa* Klaus 1964, *Triadispora epigona* Klaus 1964, *Triadispora falcata* Klaus 1964, *Triadispora plicata* Klaus 1964, *Triadispora staplinii* (Jansonius) Klaus 1964, *Vallasporites ignacii* Leschik 1956, and *Plaesiodictyon mosellanum* Wille 1970 (Fig. 10, numbers 1, 2, 3, 4, 5, 8, 13, 14, 15, 16, 17, 21). The presence of *Chordasporites singulichorda*, *Triadispora* spp. and the circumpollen species together with *Patinasporites densus* and *Vallasporites ignacii, that* have their first appearance in the base of early Carnian (e.g. Van der Eem, 1983; Kürschner and Herngreen, 2010) would indicate a Longobardian - Cordevolian transition (Ladinian - early Carnian).

Sample VBO17 was obtained from the Villabona borehole in the Transición Formation (Fig. 9, Table 2). It is represented by *Camerosporites secatus* Leschik 1956, *Classopollis zwolinskae* (Lund) Traverse 2004, *Classopollis torosus* (Reissinger) Balme 1957, *Duplicisporites granulatus* (Leschik) Scheuring 1970 and *Rhaetipollis germanicus* Schulz 1967 (Fig. 10, numbers 15, 17, 18, 19, 20). Although *Rhaetipollis germanicus* was considered a Rhaethian age taxon (Visscher and Brugman, 1981; Schulz and Heunisch, 2005), the ammonoid-dated Norian palynomorph assemblages of Svalbard provided constraints for a Norian first appearance of this taxon (Smith 1982; Cirilli, 2010). Therefore, we suggest Lacian-Aulanian age (early-middle Norian) to VBO17 assemblage because the first appearance of *Classopollis* spp. is during early Norian, and the taxa *Duplicisporites granulatus* and *Camerosporites secatus* are not registered in middle-late Norian assemblages (Visscher and Brugman, 1981; Kürschner and Herngreen 2010; Kustatscher et al., 2018).

Finally, the scarce poorly-preserved assemblage of sample Cu1 was obtained near Cueli, west of Villaviciosa (Fig. 2). This assemblage is composed of *Classopollis* spp. and *Ovalipollis pseudoalatus* (Thiergart) Schuurman 1976 and attributed a Norian-Rhaetian age (Kürschner and Herngreen, 2010).

6.2 Macroflora

Up until few years ago, no Triassic floras had been described in the Cantabrian Mountains, and all studies made reference to Permian assemblages. Permian floras had been described as "Autunian". However, Autunian is a discussed term, as it mostly refers to the early Permian (Cisuralian), yet such "Autunian flora" was described in upper Stephanian rocks (Gzhelian, late Carboniferous). For this reason, some authors (e.g., Martínez-García et al., 1991) also use the term "Stephanian-Autunian", and others (e.g., Wagner and Álvarez-Vázquez, 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) respectiverly.

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* (Sternberg) 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* (Sternberg) Kerp), *Taeniopteris* cf. *fallax* Goeppert and *Neuropteris neuropteroides* (Goeppert) Barthel.

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 Artiskian - 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 *Hyloidichnus 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, b; Martínez-García et al., 1991; 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 *Hyloidichnus 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 Sainz 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 (Demathieu and Gand, 2005). The footprints have been linked to biped animals according to their functional tridactyl II-IV pes, similar to numerous tridactyl footprints of dinosauroïd forms found in Anisian-Ladininan beds in SE France (Demathieu and Gand, 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 volcaniclastic rocks interbedded in the Permian sedimentary series.

Two types of volcaniclastic 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 characterised by coarse bedding with normal grading of pyroclast sizes. Individual levels have internal laminations or show alignments of pyroclasts. These are subangular, 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 μm to 2 mm. They are composed of ferromagnesian or feldspar microphenocrysts embedded in a fine-grained, hypocrystalline 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 amygdales.

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 (Corretgé 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, b 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 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 Fernandez-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, 2007; Gutiérrez-Claverol and Gallastegui, 2002).

In the western North Iberian continental platform, borehole Galicia-B2 at a longitude of 6.55ºW (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., *Choffatella* 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 5ºW (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 Neocomian sediments, the borehole recovered drilled 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 more than 600 m of Triassic deposits composed of two different lithostratigraphical units. The upper unit includes more than 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-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 more than 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-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 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 Martinez-Garcia, 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, b; 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 more than 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 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 rhe 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 Transicion 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.

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 Barcaíztegui (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.

References

Aller, J., Alvarez-Marrón, J., Bastida, F., Bulnes, M., Heredia, N., Marcos, A., Pérez-Estaún, A., Pulgar, J.A., Rodríguez-Fernández, L.R., 2004. Zona Cantábrica: Estructura, Deformación y Metamorfismo. In: Vera, J.A. (Ed.), Geología de España, SGE-IGME, pp. 42-47.

Alonso, J., Pulgar, J., García-Ramos, J., Barba, P., 1996. Tertiary basins and Alpine tectonics in the Cantabrian Mountains (NW Spain). In: Friend, P., Dabrio, C.J. (Eds.), Tertiary basins of Spain: the stratigraphic record of crustal kinematics. Cambridge University Press. pp.214-227.

Alonso, J.L., Marcos, A., Suárez, A., 2009. Paleogeographic inversion resulting from large out of sequence breaching thrusts: The León Fault (Cantabrian Zone, NW Iberia). A new picture of the external Variscan Thrust Belt in the Ibero-Armorican Arc. Geologica Acta 7 (4), 451-473.

Álvaro, M., Apalategui, O., Baena, J., Balcells, R., Barnolas, A., Barrera, J.L., Bellido, F., Cueto, L.A., Díaz De Neira, A., Elízaga, E., Fernández-Gianotti, J.R., Ferreiro, E., Gabaldón, V., García-Sansegundo, J., Gómez, J.A., Heredia, N., Hernández-Urroz, J., Hernández-Samaniego, A., Lendínez, A., Leyva, F., López-Olmedo, F.L., Lorenzo, S., Martín, L., Martín, D., Martín-Serrano, A., Matas, J., Monteserín, V., Nozal, F., Olive, A., Ortega, E., Piles, E., Ramírez, J.I., Robador, A., Roldán, F., Rodríguez-Fernández, L.R., Ruiz, P., Ruiz, M.T., Sánchez-Carretero, R., Teixell, A., Oliveira, J.L., Pereira, E., Ramalho, M., País, J., 1995. Mapa Geológico de la Península Ibérica, Baleares y Canarias a escala 1: 1.000.000. Instituto Tecnológico Geominero de España, Madrid.

Arthaud, F., Matte, P., 1975. Les decrochements tardi-hercyniens du sud-ouest de l'Europe, geometrie et essai de reconstitution des conditions de la deformation. Tectonophysics 25, 139–171.

Arthaud, F., Matte, P., 1977. Late Paleozoic strike-slip faulting in southern Europe and northern Africa: result of a righ-lateral shear zone between the Appalachians and the Urals. Geological Society of America Bulletin 88, 1305–1320.

Barnolas, A., Pujalte V. 2004. La Cordillera Pirenaica. In: Vera, J.A. (Ed.), Geología de España. IGME-SGE, Madrid. pp. 233–343.

Barrón, E., Gómez, J.J., Goy, A., 2001. Dataciones con palinomorfos en los materiales del tránsito Triásico–Jurásico de Poza de la Sal (Burgos). Publicaciones de Seminarios de Paleontología, Universidad de Zaragoza 5.1, 46–55.

Barrón, E., Gómez, J.J., Goy, A., 2002. Los materiales del tránsito Triásico-Jurásico en la región de Villaviciosa (Asturias, España). Geogaceta 31, 197-200.

Barrón, E., Gómez, J.J., Goy, A., Pieren, A.P., 2005. Asociaciones palinológicas del tránsito Rhaetiense–Hettangiense en Asturias (España). Geo-Temas 8, 133–136.

Barrón, E., Gómez, J.J., Goy A., Pieren, A.P., 2006. The Triassic–Jurassic boundary in Asturias (northern Spain): Palynological characterisation and facies. Review of Palaeobotany and Palynology 138, 187-208.

Boillot, G., Dupeuble, P.A., Malod, J., 1979. Subduction and Tectonics on the continental margin off northern Spain. Marine Geology 32, 53-70.

Cadenas, P., Fernández-Viejo, G., 2017. The Asturian Basin within the North Iberian margin (Bay of Biscay): seismic characterization of its geometry and its Mesozoic and Cenozoic cover. Basin Research 29 (4), 521-541. doi: 10.1111/bre.12187.

Cadenas, P., Fernández-Viejo, G., Pulgar, J.A., Tugend, J., Manatschal, G., Minshull, T.A., 2018. Constraints imposed by rift inheritance on the compressional reactivation of a hyperextended margin: mapping rift domains in the North Iberian margin and in the Cantabrian Mountains. Tectonics 37, 3, 758-785. doi:10.1002/2016TC004454.

Calvet, F., Solé de Porta, N., Salvany, J.M., 1993. Cronoestratigrafía (Palinología) del Triásico Sudpirenaico y del Pirineo Vasco-Cantábrico. Acta Geológica Hispánica 28, 33-48.

Carola, E., Muñoz, J. A., Roca, E., 2015. The transition from thick- skinned to thin- skinned tectonics in the Basque- Cantabrian Pyrenees: the Burgalesa Platform and surroundings**,** Int J Earth Sci (Geol Rundsch) 104, 2215–2239. DOI 10.1007/s00531-015-1177-z.

Castro, A., Corretgé, L.G., De la Rosa, J., Enrique, P., Martínez, F.J., Pascual, E., Lago, M., Arranz, E., Galé, C., Fernández, C., Donaire, T., López, S., 2002. Palaeozoic magmatism. In: Gibbons, W., Moreno, T. (Eds.), The Geology of Spain. Geological Society, London. pp. 117-153.

Cámara, P., 2017. Salt and Strike-Slip Tectonics as Main Drivers in the Structural Evolution of the Basque-Cantabrian Basin, Spain. In: Soto, J.I., Flinch, J.F., Tari, G. (Eds.), Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins. Tectonics and Hydrocarbon Potential. Elsevier, pp. 371-392.

Cirilli, S., 2010. Upper Triassic–lowermost Jurassic palynology and palynostratigraphy: a review, in: Lucas, S.G. (Ed.), The Triassic Time Scale. Geological Society, London, Special Publications 334, pp. 285-314.

Cohen, A.S., Thouin, C., 1987. Nearshore carbonate deposits in Lake Tanganika. Geology 15, 414-418.

Corretge, L.G., Suárez, O., Galán, G., Fernández-Suárez, J., 2004. Zona Asturoccidental-leonesa: Magmatismo. In: Vera, J.A. (Ed.) Geología de España, SGE-IGME, 63–68.

Demathieu, G., Saiz de Omeñaca, J., 1990. Primeros resultados del estudio de un nuevo yacimiento de ichnofauna triásica, en Peña Sagra (Cantabria, España). Estudios Geológicos 46, 147-150.

De la Horra, R., Cárdenes, V., Pérez-Huerta, A., González-Acebrón, L., 2012. Primera descripción de niveles con glauconita en el "Tramo de Transición", de edad Retiense (Triásico Superior), en el área de Caravia, Asturias, España. Geo-Temas 13, 103-107.

Derégnaucourt, D., Boillot, G., 1982. Carte structurale du Golfe de Gascogne á 1:2400000. In Structure géologique du Golfe de Gascogne. Bulletin du Bureau de Recherches Géologiques et Minièrs 2, 1-3, 149-178.

Escudero-Mozo, M.J., Márquez-Aliaga, A., Goy, A., Martín-Chivelet, J., López-Gómez, J., Márquez, L., Arche, A., Plasencia, P., Pla, A., Marzo, M., Sánchez-Fernández, D., 2015. Middle Triassic carbonate platforms in easter Iberia: Evolution of their fauna and palaeogeographic significance in the western Tethys. Palaeogeography, Palaeoclimatology, Palaeoecology 417, 236-260. http://dx.doi.org/10.1016/j.palaeo.2014.10.041

Ferrer, O., Roca, E., Benjumea, B., Muñoz, J.A., Ellouz, N. and Marconi Team, 2008. The deep seismic reflection MARCONI-3 profile: Role of extensional Mesozoic structure during the Pyrenean contractional deformation at the eastern part of the Bay of Biscay, Mar. Pet. Geol. 25, 714-730, doi: 10.1016/j.marpetgeo.2008.06.002.

Fillon, C., Pedreira, D., van der Beek, P.A., Huismans, R.S., Barbero, L., Pulgar, J.A.,

2016. Alpine exhumation of the central Cantabrian Mountains, Northwest Spain. Tectonics 35, 339–356, doi:10.1002/2015TC004050

Gallastegui, G., Heredia, N., Rodriguez Fernandez, L.R., Cuesta, A., 1990. El stock de Peña Prieta en el contexto del magmatismo de la Unidad del Pisuerga-Carrión (Zona Cantábrica, N de España). Cuadernos Laboratorio Xeolóxico Laxe 15, 203-217.

Gallastegui, G., Suárez, O., Cuesta, A., 2004. Zona Cantábrica: Magmatismo. In Vera, J.A. (Ed.), Geología de España, SGE-IGME, pp. 47–49.

Gallastegui, J., Pulgar, J. A., Gallart, J., 2002. Initiation of an active margin at the North Iberian continent ocean transition. Tectonics 21, 1501-1514. doi:10.1029/2001TC901046

Gand, G., 1980. Description d'une piste de Vertébré dans le Permien de L'Estérel, Var, France. Bulletin du Museum national d' Histoire Naturelle, Paris 4 (2, 4), 436-440.

Gand, G., 1987. Les traces de Vertébrés tétrapodes du Permien français Paléontologie, Stratigraphie, Paléoenvironnements. Thèse de Doctorat d'Etat ès Sciences Naturelles, Université de Bourgogne. Edit. Centre des Sciences de la Terre, Dijon, 341 p.

Gand, G., Demathieu, G., 2005. Les pistes dinosauroïdes du Trias moyen français: interprétation et révaluation de la nomenclature. Geobios 38, 725-749.

Gand, G., Kerp, H., Parsons, C., Martínez-García, E., 1997. Palaeoenvironmental and stratigraphic aspects of the discovery of animal traces and plant remains in Spanish Permian red beds (Peña Sagra, Cantabrian Mountains, Spain). Geobios 30, 295-318.

García-Espina, R., 1997. La estructura y evolución tectonoestratigráfica del borde occidental de la Cuenca Vasco-Cantábrica (Cordillera Cantábrica, NO de España). PhD Thesis, Universidad de Oviedo, 230 pp. Unpublished.

García-Mondejar, J., Pujalte, V., Robles, S., 1986. Características sedimentológicas, secuenciales y tectonoestratigráficas del Triásico de Cantabria y norte de Palencia. Cuadernos de Geología Ibérica 10, 151-172.

Gasparrini, M., Bechstädt, T., Boni, M., 2006. Massive hydrothermal dolomites in the southwestern Cantabrian Zone (Spain) and their relation to the Late Variscan evolution. Marine and Petroleum Geology 23, 543-568.

Gisbert, J., 1981. Estudio geológico-petrológico del Estefaniense-Pérmico de la Sierra del Cadí (Pirineo de Lérida): Diagénesis y sedimentología. PhD Thesis. Universidad de Zaragoza, Spain. 314 p. Unpublished.

Gómez, J.J., Goy, A., Barrón, E., 2007. Events around the Triassic–Jurassic boundary in northern and eastern Spain: A review. In: Hesselbo, S.P., McRoberts, C.A., Palfy, J (Eds.), Triassic-Jurassic Boundary events: problems, progress, possibilities. Palaeogeography, Palaeoclimatology, Palaeoecology 244, 89–110. DOI10.1016/j.palaeo.2006.06.025

Gretter, N., Ronchi, N., López-Gómez, J., De la Horra, R., Barrenechea, J., Lago, M., 2015. The Late Paleozoic-Early Mesozoic from the Catalan Pyrenees (Spain): 60 My of environmental evolution in the frame of the western peri-Tethyan palaeogeography. Palaeogeography, Palaeoclimatology, Palaeoecology 150, 679-708. http://dx.doi.org/10.1016/j.earscirev.2015.09.001

Gulliford, A.R., Flint, S.S., Hodgson, D.M., 2017. Crevasse splay processes and deposits in an ancient distributive fluvial system: The lower Beaufort Group, South Africa. Sedimentary Geology 358, 1-18. http://dx.doi.org/10.1016/j.sedgeo.2017.06.005

Gutiérrez Alonso, G., Johnston, S.T., Weil, A.B., Pastor-Galán, D., Fernández-Suárez, J., 2012. Buckling an orogen: The Cantabrian Orocline. GSA Today 4–9 http://dx.doi.org/10. 1130/GSATG141A.1.

Gutiérrez-Claverol, M., Gallastegui, J., 2002. Prospección de hidrocarburos en la plataforma continental de Asturias. Trabajos de Geología 23, 21-34.

Irvine, T.J.N., Baragar, W., 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences 8(5), 523-548.

Jammes, S., Manatschal, G., Lavier, L., 2010. Interaction between prerift salt and detachment faulting in hyperextended rift systems: The example of the Parentis and Mauleón basins (Bay of Biscay and western Pyrenees). AAPG Bulletin 94, 7, 975-957.

Julivert, M., 1971. Decollement tectonics in the Hercynian Cordillera of Northwest Spain. American Journal of Science 270-1, 1-29.

Julivert, M., Fontboté, J. M., Ribeiro, A., Conde, L. , 1972. Mapa tectónico de la Península Ibérica y Baleares, E.1:1.000.000. Inst. Geol. Min. España, Madrid.

Juncal, M., Diez., J.B., Broutin, J., Martínez-García, E., 2016. Palynoflora from the Permian Sotres Formation (Picos de Europa, Asturias, Northern Spain). Spanish Journal of Palaeontology 31 (1), 85-94.

Kelts, K., Hsü, K.J., 1978. Freshwater carbonate sedimentation. In: Lerman, A. (Ed.), Lakes: Chemistry, Geology, Physics. Springer-Verlag, Berlin. pp. 295-323.

Kürschner, W., Herngreen, G.F.W., 2010. Triassic palynology of central and northwestern Europe: a review of palynofloral diversity patterns and biostratigraphic subdivisions. In: Lucas, S.G. (Ed.), The Triassic Timescale. Geological Society, London, Special Publications, 334, pp. 263-283.

Kustatscher, E., Ash, S., Karasev, E., Pott, C., Vajda, V., Yu, J., McLoughlin, S., 2018. Flora of the Late Triassic. In: Tanner, L.H. (Ed.), The Late Triassic World, Topics in Geobiology 46, 545–622.

Lago, M., Arranz, E., Pocovi, A., Galé, C., Gil-Imaz, A., 2004a. Lower Permian magmatism of the Iberian Chain, Central Spain, and its relationship to extensional tectonics. In: Wilson, M., Neumann, E.-R., Davies, R.R., Timmerman, M.J., Heeremans, M., Larsen, B.T. (Eds.), Permo-Carboniferous Magmatism and Rifting in Europe. Geological Society, London, Special Publications 223, pp. 465-490.

Lago, M., Arranz, E., Pocovi, A., Galé, C., Gil-Imaz, A., 2004b. Permian magmatism and basin dynamics in the southern Pyrenees: a record of the transition from late Variscan transtension to early Alpine extension. In: Wilson, M., Neumann, E.-R., Davies, R.R., Timmerman, M.J., Heeremans, M., Larsen, B.T. (Eds.), Permo-Carboniferous Magmatism and Rifting in Europe. Geological Society, London, Special Publications 223, pp. 439-464.

Juez-Larré, J., Ter Voorde, M., 2009. Thermal impact of the break-up of Pangea on the Iberian Peninsula, assessed by thermochronological dating and numerical modelling. Tectonophysics 474, 200-213.

Lanaja, J.M., 1987. Contribución de la exploración petrolífera al conocimiento de la geología de España. Instituto Geológico y Minero de España, 465 p.

Lepvrier, C., Martínez-García, E., 1990. Fault development and stress evolution evolution of the post-Hercynian Asturian Basin (Asturias and Cantabria, northwestern Spain). Tectonophysics 184, 345–356.

López-Gómez, J., Arche., A., Pérez-López, A., 2002. Permian and Triassic. In: Gibbons, W., Moreno, T. (Eds.), Geology of Spain. The Geological Society, London, 195-212.

Lotze, F. (1945). Zur Gliderung der Variszíden der Iberischen Meseta. Geotekt. Forsch. 6, 78-92.

McBirney, A.R, 1984. Igneous petrology. Freeman, Cooper and Company, San Francisco, 504 p.

Mamet, B., Martínez-García, E., 1995. Permian microcodiaceans (algae, incertae sedis) Sotres Limestone, Asturias. Revista Española de Micropaleontología XXVII (3), 107-116.

Martín-González, F., Heredia, N., 2011a. Geometry, structures and evolution of the western termination of the Alpine-Pyrenean Orogen reliefs (NW Iberian Peninsula). Journal of Iberian Geology 37 (2), 103-120. https://doi.org/10.5209/rev_JIGE.2011.v37.n2.1

Martín-González, F., Heredia, N., 2011b. Complex tectonic and tectonostratigraphic evolution of an Alpine foreland basin: The western Duero Basin and the related Tertiary depressions of the NW Iberian Peninsula. Tectonophysics 502, 75-89. DOI: 10.106/j.tecto.2010.03.002

Martín-González, F., Barbero, L., Capote, R., Heredia N., Gallastegui, G., 2012. Interaction of two successive Alpine deformation fronts: constraints from low-temperature thermochronology and structural mapping (NW Iberian Peninsula). International Journal of Earth Sciences 101, 1331-1342. DOI: 10.1007/s00531-011-0712-9.

Martín-González, F., Freudenthal, M., Heredia, N., Martín-Suárez, E., Rodríguez-Fernández, R., 2014. Palaeontological age and correlations of the Tertiary deposits of the NW Iberian Peninsula: the tectonic evolution of a broken foreland basin. Geological Journal 49 (1), 15–27. http://dx.doi.org/10.1002/gj.2484.

Martinez-García, E., 1980. Hoja del Mapa Geológico de España a E. 1:50.000 nº 32 (Llanes). Segunda serie-Primera Edición (MAGNA). IGME, Madrid.

Martínez-García E., 1981. El Paleozoico de la Zona Cantábrica oriental. Trabajos de Geología 11, 95-127.

Martínez-García E., 1990. Stephanian and Permian basins. In Dallmeyer, R.D., Martínez-García, E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, pp. 39-54.

Martínez-García, E., 1991a. Orogénesis y sedimentación a finales del Paleozoico en el NE del Macizo Ibérico (Asturias, Cantabria, Palencia). Vol. Homenaje a J. Ramírez del Pozo, A.G.G.E.P., 167-174

Martínez-García E., 1991b. Hercynian syn-orogenic and post-orogenic successions in the in the Cambrian and Palentian zones (NW Spain). Comparison with other western European occurrences. Giornale di Geologia 53(1), 208-228.

Martínez-García, E., 2004. El Pérmico de Asturias. In: J.A. Vera (ed.) Geología de España, SGE-IGME, 268-269.

Martínez-García, E., Wagner, R.H., Gand, G., Villa, E., Alegre-Mateo, M.T., 2001. Permian of the Cantabrian Mountains (Asturias and Cantabria, NW Spain) and its tectonic significance. In XV Annual Field Meeting of the Association de Géologues du Permien (AGP), Oviedo, Spain, 1-64 pp.

Martínez-García, E., Coquel, R., Gutiérrez Claverol, M., Quiroga, J.L., 1998. Edad del "tramo de transición" entre el Pérmico y el Jurásico en el área de Gijón (Asturias NW de España). Geogaceta 24, 215–218.

Merino-Tomé, O.A., 2004. Estratigrafía, Sedimentología y Evolución Tectono-Sedimentaria de las Sucesiones Estefanienses en la Región de Picos de Europa. Ph.D Thesis, Universidad de Salamanca 295 pp.

Merino-Tomé, O., Villa, E., Bahamonde, J.R., Colmenero, J.R., 2006. Fusulinoidean characterization of the uppermost Moscovian-Gzhelian (upper Pennsylvanian) synorogenic depositional sequences from northern Picos de Europa Unit (Spain). Facies 52, 521-540. doi: 10.1007/s10347-006-0046-4

Merino-Tomé, O.A., Bahamonde, J.R., Fernández, L.P., Colmenero, J.R., 2007. Facies architecture and cyclicity of an Upper Carboniferous carbonate ramp developed in a Variscan piggy-back basin (Cantabrian Mountains, NW Spain). In Nichols, G., et al. (eds.) Sedimentary Processes, Environments and Basins: A Tribute to Peter Friend. International Association of Sedimentologists Special Publication 38, 183-217.

Merino-Tomé, O., Bahamonde, J.R., Colmenero, J.R., Heredia, N., Villa, E., Farias, P., 2009. Emplacement of the Cuera and Picos de Europa imbricate system at the core of the Ibero-Armorican arc (Cantabrian Zone, N Spain): new precisions concerning the timing of arc closure. Geological Society of America Bulletin 121, 729-751.

Merino-Tomé, O., Gutierrez-Alonso, G., Villa, E., Fernández-Suárez, J., Martín-Llaneza, J., Hofmann, M., 2017. LA-ICP-MS U-Pb dating of Carboniferous ash layers in the Cantabrian Zone (N Spain): Stratigraphic implications. Journal of the Geological Society 174, 836-849.

Miall, A.D., 1985. Architectural-element analysis: a new method for facies analysis applied to fluvial deposits. Earth Science Reviews 22, 261-308.

Miall, A.D., 1996. The Geology of Fluvial Deposits. Sedimentary Facies, Basin Análisis and Petroleum Geology. Springer. Berlin. 582 p.

Miall, A.D., 2014. Fluvial Depositional Systems. Springer. Berlin. 316 p.

Michel L.A., Tabor N.J., Montañez I.P., Schmitz M.D., Davydov V.I., 2015. Chronostratigraphy and Paleoclimatology of the Lodève Basin, France: Evidence for a pan-tropical aridification event across the Carboniferous–Permian boundary. Palaeogeography, Palaeoclimatology, Palaeoecology 430, 118–131.

Mujal, E., Gretter, N., Ronchi, A., López-Gómez, J., Falconnet, J., Díez, J.B., De la

Horra, R., Bolet, A., Oms, O., Arche, A., Barrenechea, J.F., Steyer, J.S., Fortuny, J., 2016. Constraining the Permian/Triassic transition in continental environments: stratigraphic and paleontological record from the Catalan Pyrenees (NE Iberian Peninsula). Palaeogeography, Palaeoclimatology, Plaeoecology 445, 18-37. http://dx.doi.org/10.1016/j.palaeo.2015.12.008

Navarro, D., 1984. Hoja del Mapa Geológico de España a E. 1:50.000 nº 31 (Ribadesella). Segunda serie-Primera Edición (MAGNA). IGME, Madrid.

Patac, I., 1920. La Formación Uraliense Asturiana. Estudios de Cuencas Carboníferas. Artes Gráficas, Gijón, 50 pp.

Pedreira, D., Pulgar, J.A., Gallart, J., Torne, M., 2007. Three-dimensional gravity and magnetic modeling of crustal indentation and wedging in the western Pyrenees-Cantabrian Mountains. Journal of Geophysical Research, 112. http://dx.doi.org/10. 1029/2007JB005021.

Pellenard, P., Gand, G., Schmitz, M., Galtier, J., Broutin, J., Stéyer, J.-S., 2017. High-precision U-Pb zircon ages for explosive volcanism calibrating the NW European continental Autunian stratotype. Gondwana Research 51, 118–136.

Pereira, M. F., Castro, A., Chichorro, M., Fernández, C., Diaz-Alvarado, J., Marti, J., Rodriguez, C., 2014, Chronological link between deep-seated processes in magma chambers and eruptions: Permo-Carboniferous magmatism in the core of Pangaea (Southern Pyrenees). Gondwana Research 25(1), 290-308.

Pérez-Estaún, A., Martínez-Catalán; J.R., Bastida, F., 1991. Crustal thickenning and deformation sequence in the footwall to the suture of the Variscan belt of northwest Spain. Tectonophysics 191, 243-253.

Perini, G., Timmerman, M. J., 2008. Permian $^{40}Ar/^{39}Ar$ ages for post-Variscan minor intrusions in the Iberian Range and Spanish Central System. Geologica Acta 6(4), 335-344.

Pieren, A., Areces, J., Toraño, J., Martínez-García, E., 1995. Estratigrafía y estructura de los materiales permotriásicos del sector Gijón-La Camocha (Asturias). Cuadernos de Geología Ibérica 19, 309-335.

Pulgar, J. A., Alonso, J. L., Espina, R. G., Marín, J. A., 1999. La deformación alpina en el basamento varisco de la Zona Cantábrica. Trabajos de Geología 21, 283-294.

Roca, E., Muñoz, J.-A., Ferrer, O., Ellouz, N., 2011. The role of the Bay of Biscay Mesozoic extensional structure in the configuration of the Pyrenean orogen: Constraints from the MARCONI deep seismic reflection survey. Tectonics 30, TC2001. http://dx.doi. org/10.1029/2010TC002735.

Robles, S., 2004. El Pérmico de la Cuenca Vasco-Cantábrica. In: J.A. Vera (Ed.), Geología de España, SGE-IGME, 269-271.

Robles, S., Pujalte, V., 2004. El Triásico de la Cordillera Cantábrica. In: J.A. Vera (Ed.), Geología de España, SGE-IGME, 274-276.

Rodríguez-Fernández, L.R., Heredia, N., 1987. La estratigrafía del Carbonífero y la estructura de la Unidad del Pisuerga-Carrión. Cadernos Laboratorio Xeolóxico Laxe 12, 207-229.

Rodríguez Fernández, L.R., Fernández, L.P., N. Heredia, N. , 2002. Carboniferous of the Pisuerga-Carrión Unit. In: García-López S., Bastida, F. (Eds.), Paleozoic conodonts from Northern Spain. Cuadernos del Museo Geominero 1, 93-104.

Roest, W. R., Srivastava, S. P., 1991. Kinematics of the plate boundaries between between Eurasia, Iberia and Africa in the North-Atlantic from the Late Cretaceous Cretaceous to the present. Geology 19, 613–616. https://doi.org/10.1130/0091-7613

Saiz de Omeñaca, J., 1977. Estratigrafía y sedimentología del Triásico de Cantabria. PhD Theis. Universidad de Oviedo, 500 p. Unpublished.

Salas, R., Casas, A., 1993. Mesozoic extensional tectonics, stratigraphy and crustal evolution during the Alpine cycle of the eastern Iberian basin. Tectonophysics 228, 33–55.

Salvany, J.M., 1990a. El Keuper del Diapiro de Poza de la Sal (Burgos). In: Ortí Cabo, F., Salvany Durán, J.M. (Eds.), Formaciones evaporíticas de la Cuenca del Ebro y cadenas periféricas y de la zona de Levante. Nuevas aportaciones y guía de superficie. ENRESA-GPPG, Barcelona, España, pp. 21–28.

Salvany, J.M., 1990b. Parada 18: Diapiro de Poza de la Sal (Keuper). In: Ortí Cabo, F., Salvany Durán, J.M. (Eds.), Formaciones evaporíticas de la Cuenca del Ebro y cadenas periféricas, y de la zona de Levante. Nuevas aportaciones y guía de superficie. ENRESA-GPPG, Barcelona, España, pp. 196–198.

Sánchez-Moya, Y., Barrón, E., Sopeña, A., 2005. Nuevos datos sobre la edad del Buntsandstein de la Cordillera Cantábrica. XV Congreso Nacional de Sedimentología y IV Coloquio de Estratigrafía y Paleontografía del Pérmico y Triásico de España. Geo-Temas 8, 251-253.

Sánchez-Martínez, S., de la Horra, R., Arenas, R., Gerdes, A., Galán-Abellán, A.B., López-Gómez, J., Barrenechea, J.F., Arche. A., 2012. U-Pb Ages of Detrital Zircons from the Permo-Triassic Series of the Iberian Ranges: A Record of Variable Provenance during Rift Propagation. Journal of Geology 120, 135-154.

Schulz, E., Heunisch, C., 2005. Palynostratigraphische Gliederungsmöglichkeiten des deutschen Keupers. In: Beutler, G., Hauschke, N., Nitsch, E., Vath., U. (Eds.), Stratigraphie von Deutschland IV: Keuper. Courier Forschungsinstitut Senckenberg 253, pp. 296

Sibuet, J. C., Srivastava, S. P., Spakman, W., 2004. Pyrenean orogeny and plate plate kinematics. Journal of Geophysical Research 109, B0 B08104.https://doi.org/10.1029/2003JB002514

Smit, P.W., 1966. Sedimentprtrografie en milieu analyse van de Permo-Trias afzettingen langs de ooste lijke rand van het Cantabrische gebergte (Spanje). Internal Report, Leiden University, The Netherlands.

Smith, D.G., 1982. Stratigraphic significance of a palynoflora from ammonoid-bearing Early Norian strata in Svalbard. Newsletters on Stratigraphy 11, 154–161.

Sopeña, A., Sánchez-Moya, Y., Barrón, E., 2009. New palynological and isotopic data for the Triassic of the western Cantabrian Mountains (Spain). Journal of Iberian Geology 35 (1), 35-45.

Stampfli, G.M., Kozur, H.W., 2006. Europe from the Variscan to the Alpine cycles. In: Gee, D.H., Stephenson, R.A. (Eds.), European Lithosphere Dynamics. Geological Society, London, Memoirs 32, 57-82.

Suárez-Rodríguez, A., 1988. Estructura del área de Villaviciosa-Libardón (Asturias, Cordillera Cantábrica). Trabajos de Geología 17, 87-98.

Suárez-Vega, L.C. ,1969. Las series Preliásicas. E1 tramo de transición. El límite Trías-lias en España. Seminarios de Estratigrafía, Publ. Fac. de Ciencias de la Univ. de Madrid 4, 41-46.

Suárez-Vega, L.C., 1974. Estratigrafía del Jurásico de Asturias. Cuadernos de Geología Ibérica 3, 1–368.

Symons, D.T.A., Kawasaki, K., Tornos, F., Velasco, F., Rosales, I, 2017. Temporal constraints on genesis of the Caravia-Berbes fluorite deposits of Asturias, Spain, from paleomagnetism. Ore Geology Reviews 80, 754–766.

Teixell, A., Labaume, P.,Avarza, P., Espurt, N., de Saint Blanquat, M., Lagabrielle, Y., 2018. Crustal structure and evolution of the Pyrenean-Cantabrian belt: A review and new interpretations from recent concepts and data. Tectonophysics 724-725, 146-170.

Thinon, I., Matias, L., Réhault, J. P., Hirn, A., Fidalgo-Gonzalez, L., Avedik Avedik, F., 2003. Deep structure of the Armorican Basin (Bay of Biscay): A review of Norgasis seismic reflection and refraction data. Journal of the Geological Society 160, 99–116.

Tornos, F., Delgado, A., Casquet, C., Galindo, C., Reyes, E., 1996. La evolución isotópica de los fluidos ligados a los sistemas hidrotermales tardi- y postvariscos del Sistema Central Español. Geogaceta 20 (7), 1501-1504.

Tugend, J., Manatschal, G., Kusznir, N.J., Masini, E., Mohn, G., Thinon, I., 2014. Formation and deformation of hyperextended rift systems: Insights from rift domain mapping in the Bay of Biscay-Pyrenees. Tectonics 33, 1239-1276. doi: 10.1002/ 2014TC003529.

Ubide, T., Wijbrans, J.R., Galé, C., Arranz, E., Lago, M., Larrea, P., 2014. Age of the Cretaceous alkaline magmatism in northeast Iberia: implications for the Alpine cycle in the Pyrenees. Tectonics 33, 1444–1460. http://dx.doi.org/10.1002/2013TC003511.

Uzkeda, H., Bulnes, M., Poblet, J., García-Ramos, J. C., Piñuela, L., 2016. Jurassic extension and Cenozoic inversion tectonics in the Asturian Basin

Basin, NW Iberian Peninsula: 3D structural model and kinematic evolution. Journal Journal of Structural Geology 90, 157–176.

Valverde-Vaquero, P., 1992. Permo-Carboniferous magmatic activity in the Cantabrian Zone (NE Iberian Massif, Asturias, NW Spain). MSc Thesis, Boston College, USA, 198 pp.

Van Der Eem, J.G.L.A., 1983. Aspects of Middle and Late Triassic Palynology: 6. Palynological investigations in the Ladinian and Lower Karnian of the Western Dolomites, Italy. Review of Palaeobotany and Palynology 39, 189-300.

Velando, F., Castelló, R., Orviz, F., Ortuño, G, Caride, C., Gervilla, M., Fernández-Pello, J., Obis, A., 1975. Hoja del Mapa Geológico de España E. 1:50.000 nº 53 (Mieres). Segunda serie MAGNA-Primera edición. IGME, 36 pp.

Vergés, J., García-Senz, J., 2001. Mesozoic evolution and Cainozoic inversion of the Pyrenean Rift. In: Ziegler, P.A., Cavazza, W., Robertson, A.H.F., Crasquin-Soleau, S. (Eds.), Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins. Mem. Mus. Nac. Hist. Nat. 186, 187-212.

Visscher, H., Brugman, W.A., 1981. Ranges of selected palynomorphs in the Alpine Triassic of Europe. Review of Palaeobotany and Palynology 34, 115-128.

Wagner, R.H., Martínez-García, E., 1982. Description of an early Permian flora from Asturias and comments on similar occurrences in the Iberian Península. Trabajos de Geología 12, 273-287.

Weil, A.B., 2006. Kinematics of orocline tightening in the core of an arc: paleomagnetic analysis of the Ponga Unit, Cantabrian Arc, northern Spain. Tectonics 25, 3, TC3012. doi 10.1029/2005TC001861

Weil, A.B., Gutiérez-Alonso, G., Johnston, S.T., Pastor-Galán, D., 2016. Kinematic constraints on buckling a lithospheric-scale orocline along the northern margin of Gondwana: A geologic synthesis. Tectonophysics 582, 25-49. doi: 10.1016/j.tecto.2012.10.006

Wood, D.G., Gabriel, A.M., Lawson, J.C., 1996. Palynological techniques – processing and microscopy. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: Principles and applications. AASP Foundation 1, 29-50.

Wagner, R.H., Álvarez-Vázquez, C., 2010. The Carboniferous floras of the Iberian Peninsula: A synyhesis with geological connotations. Review of Paleobotany and Palynology 162, 339-324.

Zamora, G., Fleming, M., Gallastegui, J. 2017. Salt Tectonics within the offshore Asturian Basin: North Iberian margin. In Soto, J.I., Flinch, J.F., Tari, G. (Eds.), Permo-Triassic salt provinces of Europe, North Africa and the Atlantic Margins. Elsevier, Amsterdam, pp. 352-368.

Ziegler, P.A., 1988. Post-Hercynian plate reorganization in the Tethys and Artic-North Atlantic domains. In: W. Manspeizer (Ed.), Triassic-Jurassic Rifting. Continental Breakup and the Origin of the Atlantic Ocean and Passive Margins. Developments in Geotectonics 22, 711-755. Part B. Elsevier. Amsterdam.

Ziegler, P.A., 1993. Late Paleozoic-Early Mesozoic plate reorganization: evolution and demise of the Variscan fold belt. In: Ramer, J.F., Neubauer, F. (Eds.), Pre-Mesozoic Geology in the Alps. Springer Verlag, Berlin, pp. 203-216.

Ziegler, P.A., Stampfli, G.M., 2001. Late Paleozoic-Early Mesozoic plate boundary reorganization: collapse of the Variscan orogen and opening of the Neotethys. Natura Bresciana 27, 17-34.

Ziegler, P.A., Dèzes, P., 2006. Crustal evolution of Western and Central Europe. In: Gee, D.H., Stephenson, R.A. (Eds.), European Lithosphere Dynamics. Geological Society, London, Memoirs 32, 43-56.

Figure 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. See location in figure 1a. Schematic geological cross-sections 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.

Figure 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 figure 2a.

Figure 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).

Figure 4. Studied stratigraphic sections and log of the Villabona borehole. Sections include differentiated lithostratigraphical units, architectural elements (abbreviations refer to figure 7) and locations of our palaeontological data (see also Table 2 for more detailed location of the palaeontological data in the studied sectios and the different formations). See figure 1b for the location of the sections. Geographical location of the sections: Villabona: 43º27´50´´, 5º50´18´´; Frieres: 43º20´40´´, 5º44´20´´; Acebal: 43º19´40´´, 5º42´20´´; Sotres: 43º14´09´´, 4º44´18´´; Cicera: 43º14´10´´, 4º34´12´´; Peña Sagra: 43º02´18´´, 4º26´15´´; Rueda: 42º51´30´´, 4º24´40´´; Carmona: 43º16´50´´, 4º20´18´´; Riocorvo: 43º16´12´´, 3º54´12´´.

Figure 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.

Figure 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.

Figure 7. Differentiated facies, facies associations and defined architectural elements. Vertical location of the architectural elements in the studied sections are shown in figure 4. Representative field pictures of the architectural elements are provided in figure 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, volcaniclastic and marine origin.

Figure 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 figure 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, volcaniclastic and marine origin.

Figure 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.

Figure 10. Representative pollen specimens of the differents 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. *Microcachryidites fastidioides*, 11. *Microcachryidites 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. *Plaesiodictyon mosellanum*. See text for the locations of the specimens in the assemblages and the formations, and figure 4 and Table 2 for their location in the sections.

Figure 11. *Supaia* sp. specimen. Base of the Sotres Formation of the Peña Sagra - La Cohilla section. See figures 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).

Figure 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 figures 4, 9 18, and Table 2 for stratigraphic locations. Both footprints were obtained in fine sandstone beds.

Figure 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 meters. See also Acebal - P. Siero section in figure 4.

Figure 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 figure 15A, B.

Figure 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 figure 14.

Figure 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.

Figure 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 figure 16 to compare the change of basin configurations from the Permian to Triassic.

Figure 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 (1973); 4- Martínez-García (1991a); 5- Martínez-García (1991b); 6- De la Horra et al. (2012); 7- Manjón and Gutiérrez-Claverol (1991); 8- Martínez-García et al. (1991); 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.

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 (1973); 4- Martínez-García (1991a); 5- Martínez-García (1991b); 6- De la Horra et al. (2012); 7- Manjón and Gutiérrez-Claverol (1991); 8- Martínez-García et al. (1991); 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).

Table 2. Location in the formations and the studied sections of the palaeontological samples obtained in this work (palynological associations, macroflora and footprints).

The asterisc indicates a sample obtained by De la Horra et al. (2012). See also figures 4 and 9.

Highlights

- The beginning of the Alpine cycle in the Cantabrian Mountains has been erroneously interpreted within a specific geodynamic context far from the well-known general evolutionary stages of same-age western Peri-Tethys basins.
- Through detailed multidisciplinary field work, including new palaeontological data, this study defines new lithostratigraphical units and five new tectono-sedimentary cycles (TS I-V) in the Cantabrian Mountains.
- Generalized karstification in the basin of palaeogeographical significance represents the end of Permian deposition in the Cantabrian Mountains, and this was followed by more than 30 Ma of no sedimentation.
- As our main contribution to the field, the TS I-V units defined point to a common post-Variscan to early Alpine tectono-sedimentary evolution for the whole Pyrenean-Cantabrian realm.

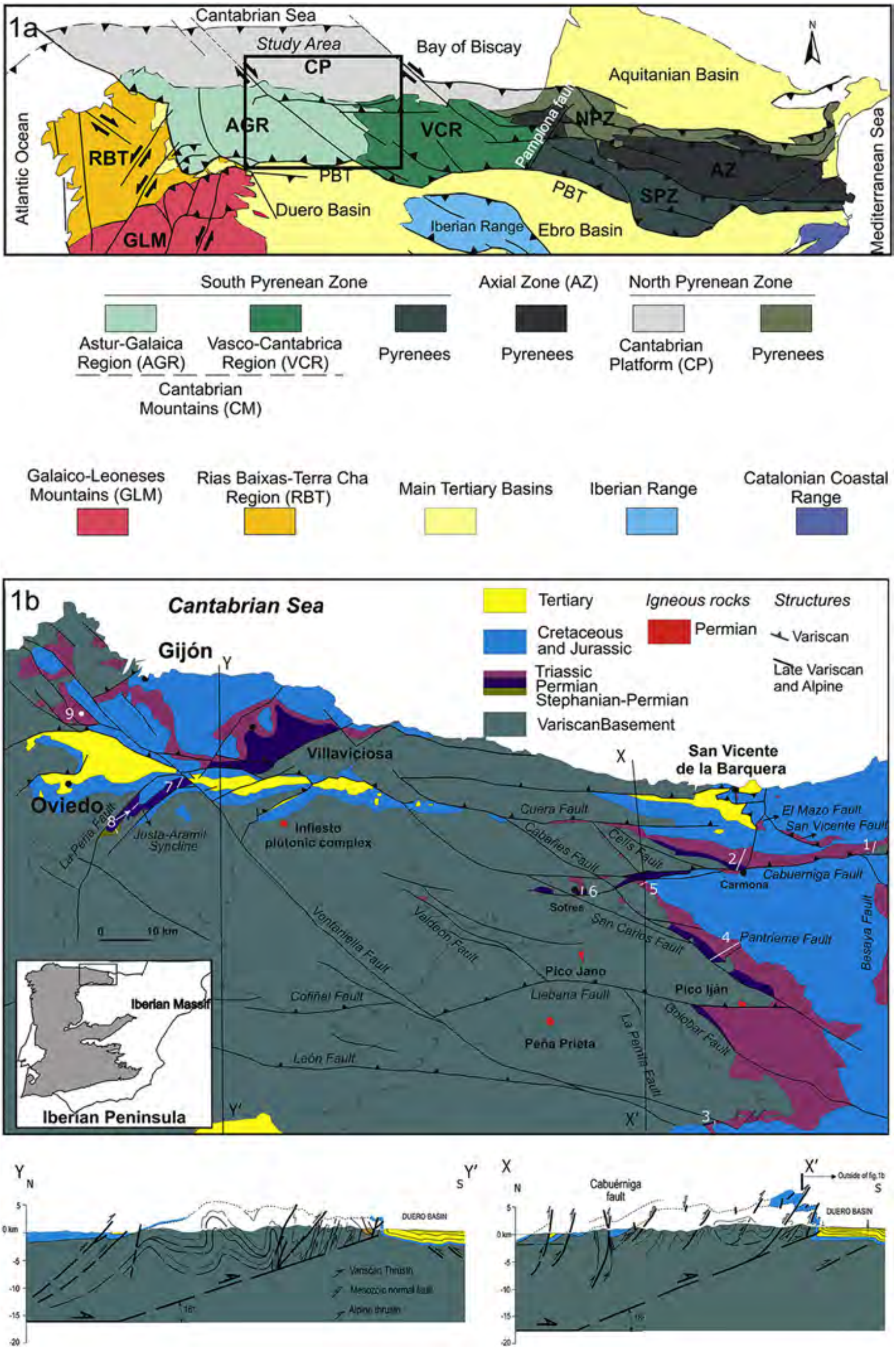

1a
Cantabrian Sea
Study Area
CP
Bay of Biscay
Aquitanian Basin
Atlantic Ocean
AGR
RBT
VCR
NPZ
Pamplona fault
AZ
SPZ
PBT
Duero Basin
GLM
Iberian Range
Ebro Basin
Mediterranean Sea
N
South Pyrenean Zone
Axial Zone (AZ)
North Pyrenean Zone
Astur-Galaica Region (AGR)
Vasco-Cantabrica Region (VCR)
Pyrenees
Pyrenees
Cantabrian Platform (CP)
Pyrenees
Cantabrian Mountains (CM)
Galaico-Leoneses Mountains (GLM)
Rias Baixas-Terra Cha Region (RBT)
Main Tertiary Basins
Iberian Range
Catalonian Coastal Range
1b
Cantabrian Sea
Tertiary
Cretaceous and Jurassic
Triassic
Permian
Stephanian-Permian
VariscanBasement
Igneous rocks
Permian
Structures
Variscan
Late Variscan and Alpine
Gijón
Y
9
Villaviciosa
X
San Vicente de la Barquera
Oviedo
7
8
La Peña Fault
Justa-Aramil Syncline
Infiesto plutonic complex
Cuera Fault
El Mazo Fault
San Vicente Fault
Cabañes Fault
Celis Fault
1
2
Cabuerniga Fault
Carmona
6
5
Sotres
San Carlos Fault
4
Pantrieme Fault
Besaya Fault
0
10 km
Ventaniella Fault
Valdeón Fault
Pico Jano
Pico Ijàn
Cofiñel Fault
Liebana Fault
La Peña Fault
Golobar Fault
Peña Prieta
León Fault
Iberian Massif
Iberian Peninsula
Y'
X'
3
Y
N
S
Y'
5
0 km
-5
-10
-15
-20
DUERO BASIN
Variscan Thrusts
Mesozoic normal fault
Alpine thrusts
16°
X
N
Cabuérniga fault
X'
Outside of fig.1b
S
DUERO BASIN
5
0 km
-5
-10
-15
-20
16°

Figure 1

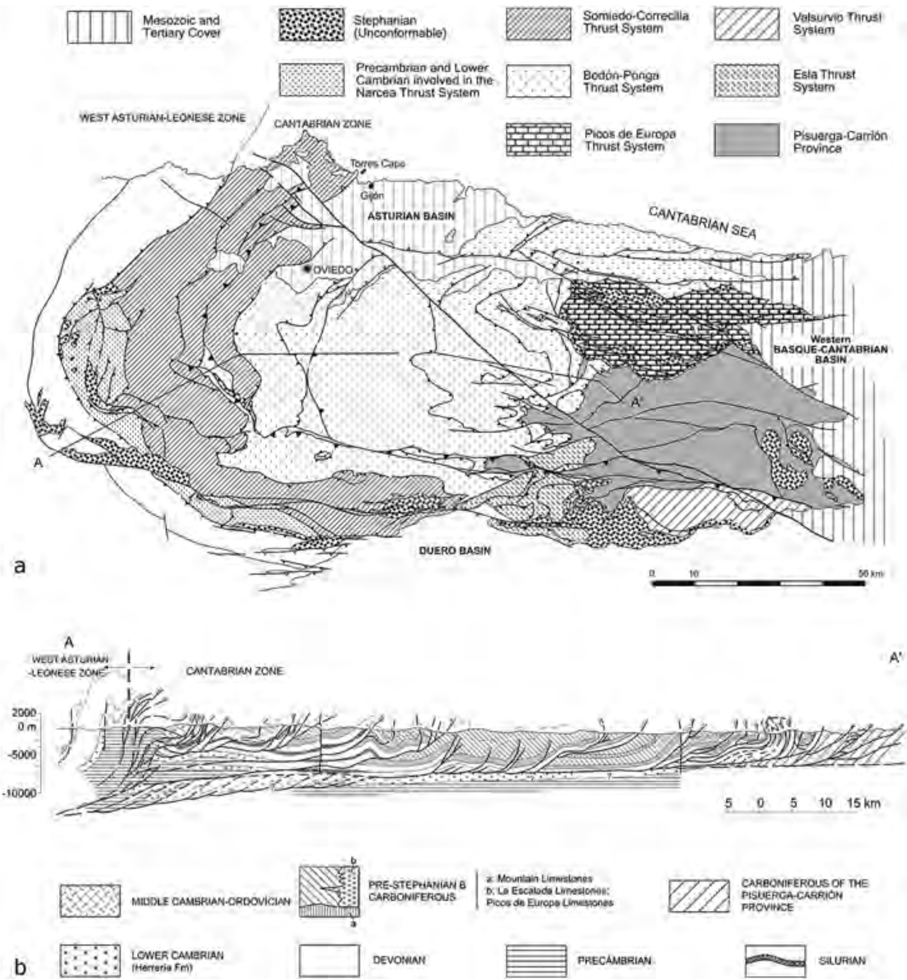
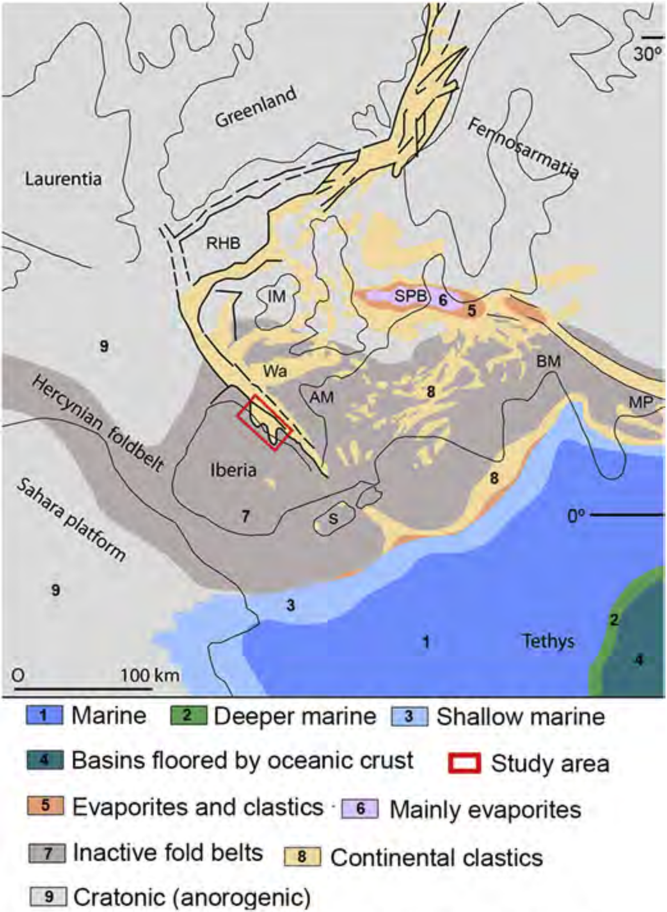

Mesozoic and Tertiary Cover
Stephanian (Unconformable)
Somiedo-Correcilla Thrust System
Valsurvio Thrust System
Precambrian and Lower Cambrian involved in the Narcea Thrust System
Bodón-Ponga Thrust System
Esla Thrust System
Picos de Europa Thrust System
Pisuerga-Carrión Province
WEST ASTURIAN-LEONESE ZONE
CANTABRIAN ZONE
Torres Cape
Gijón
ASTURIAN BASIN
CANTABRIAN SEA
OVIEDO
Western BASQUE-CANTABRIAN BASIN
A
A'
DUERO BASIN
a
b
WEST ASTURIAN -LEONESE ZONE
CANTABRIAN ZONE
2000
0 m
-5000
-10000
5 0 5 10 15 km
MIDDLE CAMBRIAN-ORDOVICIAN
PRE-STEPHANIAN B CARBONIFEROUS
a: Mountain Limestones
b: La Escalada Limestones; Picos de Europa Limestones
CARBONIFEROUS OF THE PISUERGA-CARRIÓN PROVINCE
LOWER CAMBRIAN (Herreria Fm)
DEVONIAN
PRECAMBRIAN
SILURIAN

Figure 2



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

Figure 3

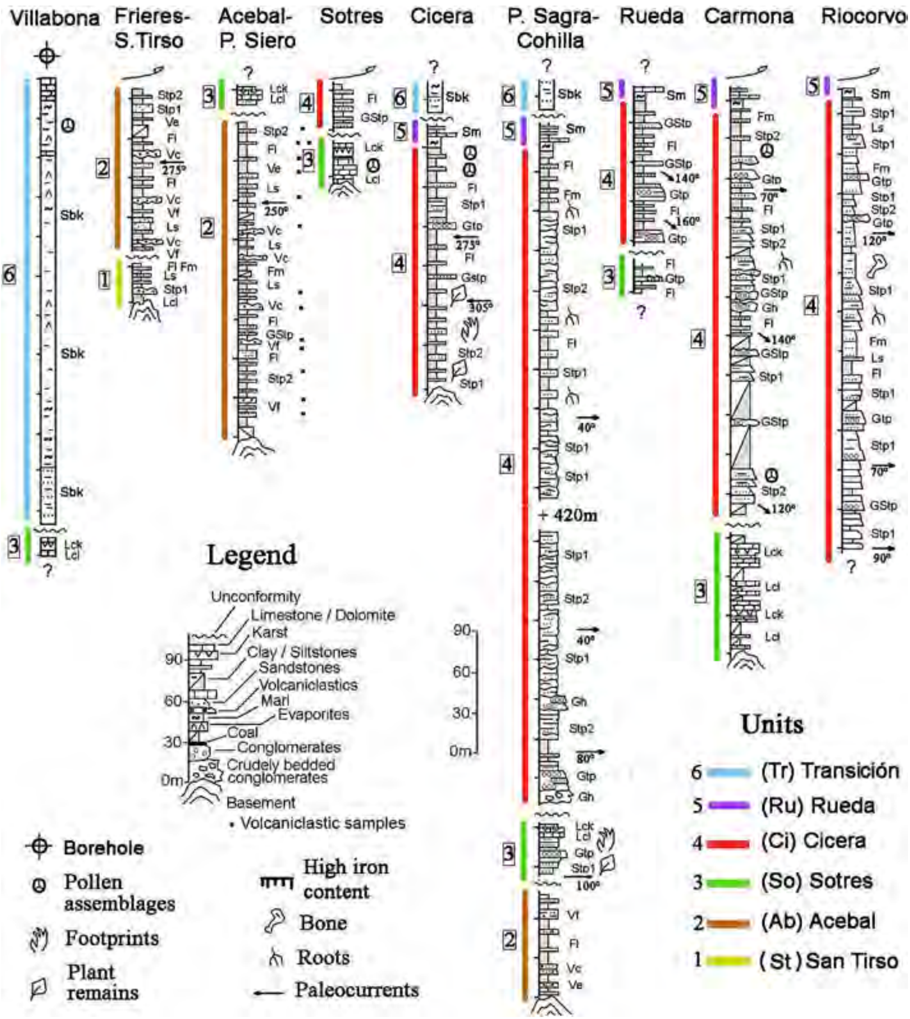
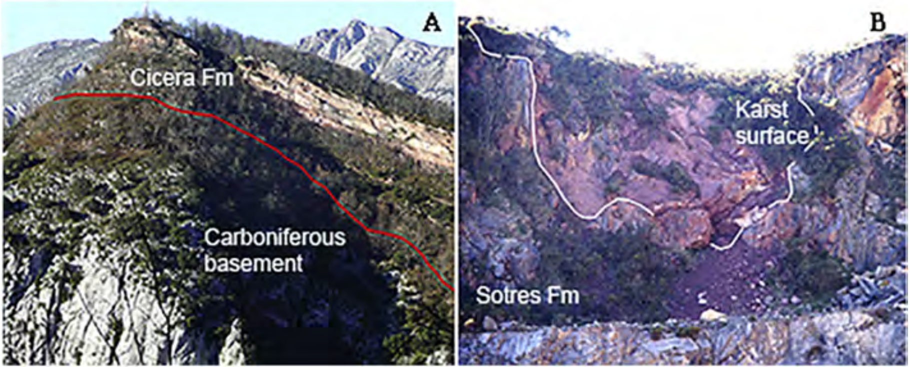

Villabona
Frieres-S.Tirso
Acebal-P. Siero
Sotres
Cicera
P. Sagra-Cohilla
Rueda
Carmona
Riocorvo
+ 420m
Legend
Unconformity
Limestone / Dolomite
Karst
Clay / Siltstones
Sandstones
Volcaniclastics
Marl
Evaporites
Coal
Conglomerates
Crudely bedded conglomerates
Basement
• Volcaniclastic samples
Borehole
Pollen assemblages
Footprints
Plant remains
High iron content
Bone
Roots
Paleocurrents
Units
6 (Tr) Transición
5 (Ru) Rueda
4 (Ci) Cicera
3 (So) Sotres
2 (Ab) Acebal
1 (St) San Tirso

Figure 4

Figure 5



A
Cicera Fm
Carboniferous basement
B
Karst surface
Sotres Fm

Figure 6

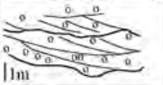
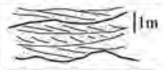
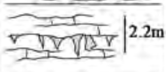
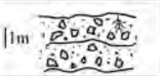
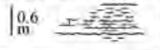
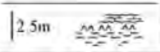
Origin	Code	Architectural element and Facies associations	Description (facies)	Interpretation	Location (Sections)
Fluvial	Gh		Clast-supported. Crudely bedded gravel and imbrication.	**Longitudinal bedforms. Sieve deposits.**	La Cohilla Peña Sagra
Fluvial	Gtp		Clastic supported bedded gravel. Trough and planar cross-beds.	**Gravel bars and bedforms** in minor fluvial channel fill.	Cohilla Rueda Carmona Peña Sagra
Fluvial	GStp		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
Fluvial	Stp1		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
Fluvial	Stp2		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
Fluvial	Fl		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
Fluvial	Fm		Massive mud-silt with desiccation craks and roots (sometimes eroded)	**Overbank-abandoned channel**	Cicera, Rueda, Acebal, Cohilla Carmona
Lacustrine and playa lake	Ls		Fine laminated sand and silt with disiccation craks and plant remains	**Laminated sand and silt** of accumulated playa deposits.	Rueda Acebal Carmona
Lacustrine and playa lake	Lc1		Fine-medium laminated (ondulated-organic) grey carbonate lamina on green massive marls	**Laminated carbonates** and marls Accumulated lacustrine deposits	Peña Sagra Carmona
Lacustrine and playa lake	Lck		Medium-thick laminated strata grey carbonate with karst carbonate	**Karst into laminated carbonates** Interruption and karstification of lacustrine deposits	Carmona
Volcaniclastics	Vf		Graded pyroclastic lapilli-breccia deposits	**Pyroclastic airfall** Fall-out of volcanic fragments (tephra)	Friere Acebal
Volcaniclastics	Vc		Medium to thick structureless. Possible reverse gradded	**Pyroclastic flow** Turbulent flow of volcanic debris	Friere Acebal
Volcaniclastics	Ve		Reworking of volcaniclastic material with soft structure	**Epiclastic flow.** Mostly fluvial transported	Friere Acebal
Shallow marine	Sm		Succession of marls and limestones with ripples and algal lamination, and siltstones	**Shallow marine. Inter-supratidal. Mixed sediments.**	Cicera, Rueda, Cohilla, Carmona
Sabkha	Sbk		Successions of poorly organized siltstones, marls, gypsum and limestones beds	**Marine sabkha. Transitional area. Mixed sediments.**	Cicera, Cohilla, Villabona

Figure 7

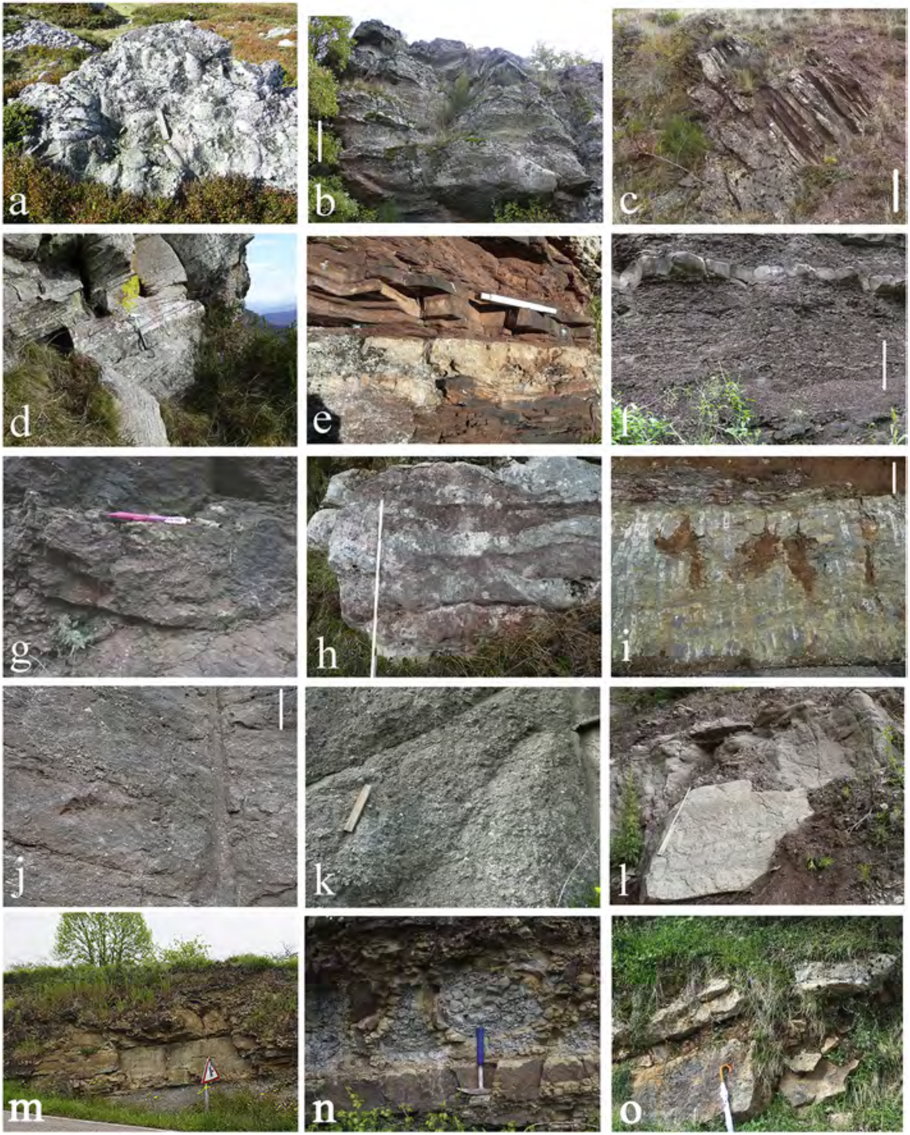


Figure 8

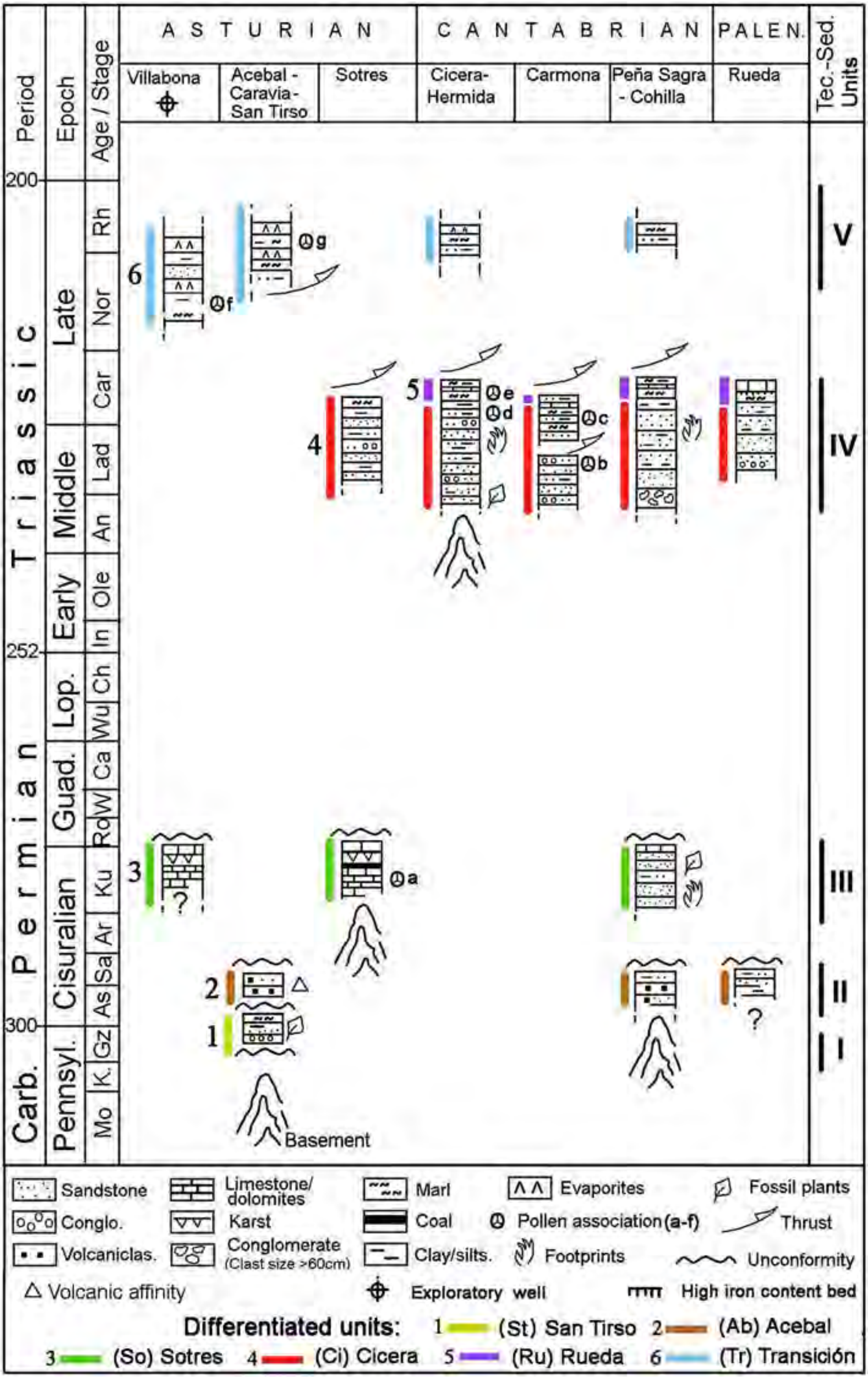

Period
Epoch
Age / Stage
ASTURIAN
CANTABRIAN
PALEN.
Tec.-Sed. Units
Villabona
Acebal - Caravia - San Tirso
Sotres
Cicera-Hermida
Carmona
Peña Sagra - Cohilla
Rueda
200
252
300
Triassic
Late
Middle
Early
Rh
Nor
Car
Lad
An
Ole
In
Permian
Lop.
Guad.
Cisuralian
Ch
Wu
Ca
W
Ro
Ku
Ar
Sa
As
Carb.
Pennsyl.
Gz
K.
Mo
V
IV
III
II
I
Basement
Sandstone
Conglo.
Volcaniclas.
Limestone/ dolomites
Karst
Conglomerate (Clast size >60cm)
Marl
Coal
Clay/silts.
Evaporites
Pollen association (a-f)
Footprints
Fossil plants
Thrust
Unconformity
Volcanic affinity
Exploratory well
High iron content bed
Differentiated units:
1 (St) San Tirso
2 (Ab) Acebal
3 (So) Sotres
4 (Ci) Cicera
5 (Ru) Rueda
6 (Tr) Transición

Figure 9

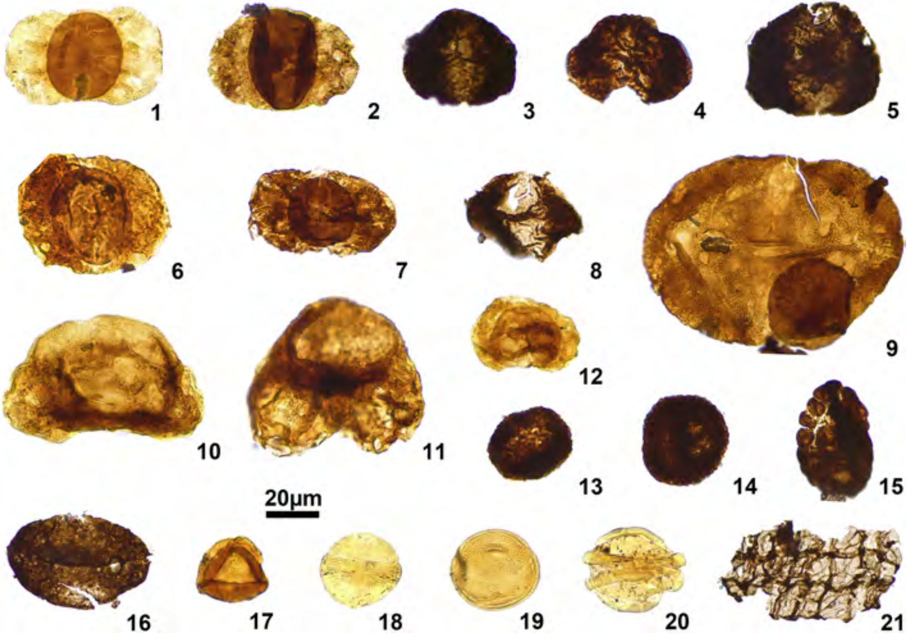


Figure 10

Figure 11

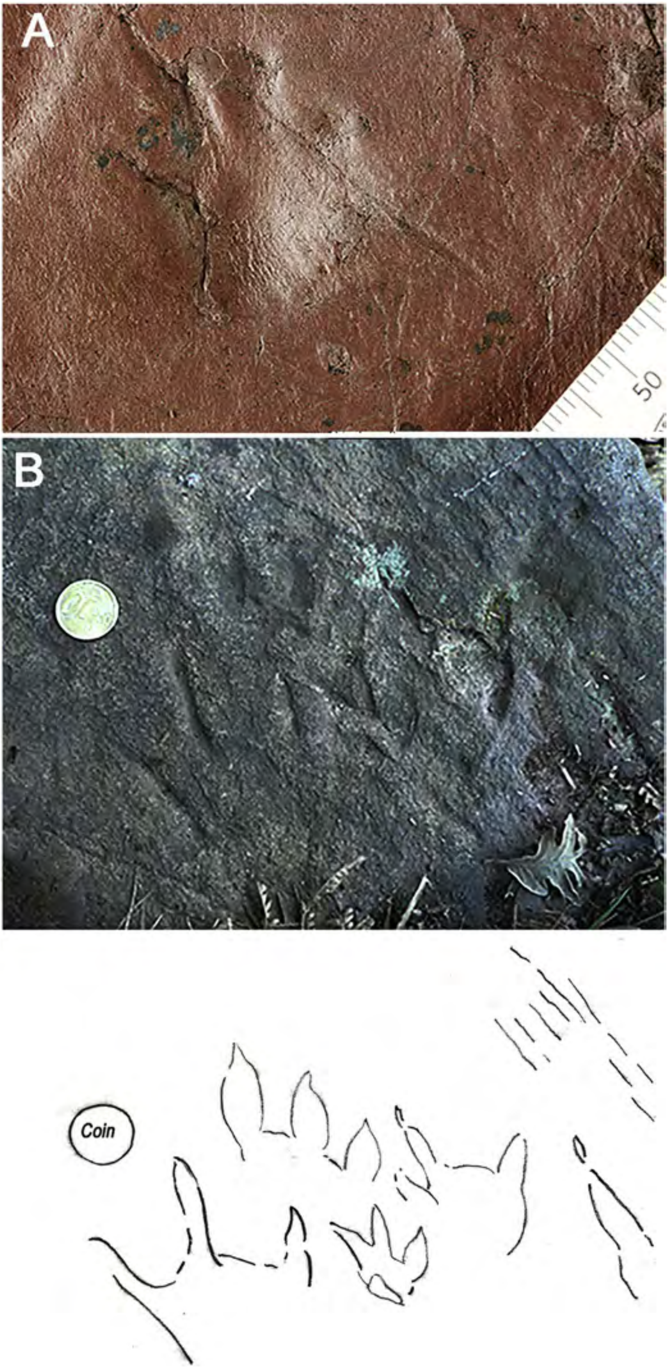


Figure 12

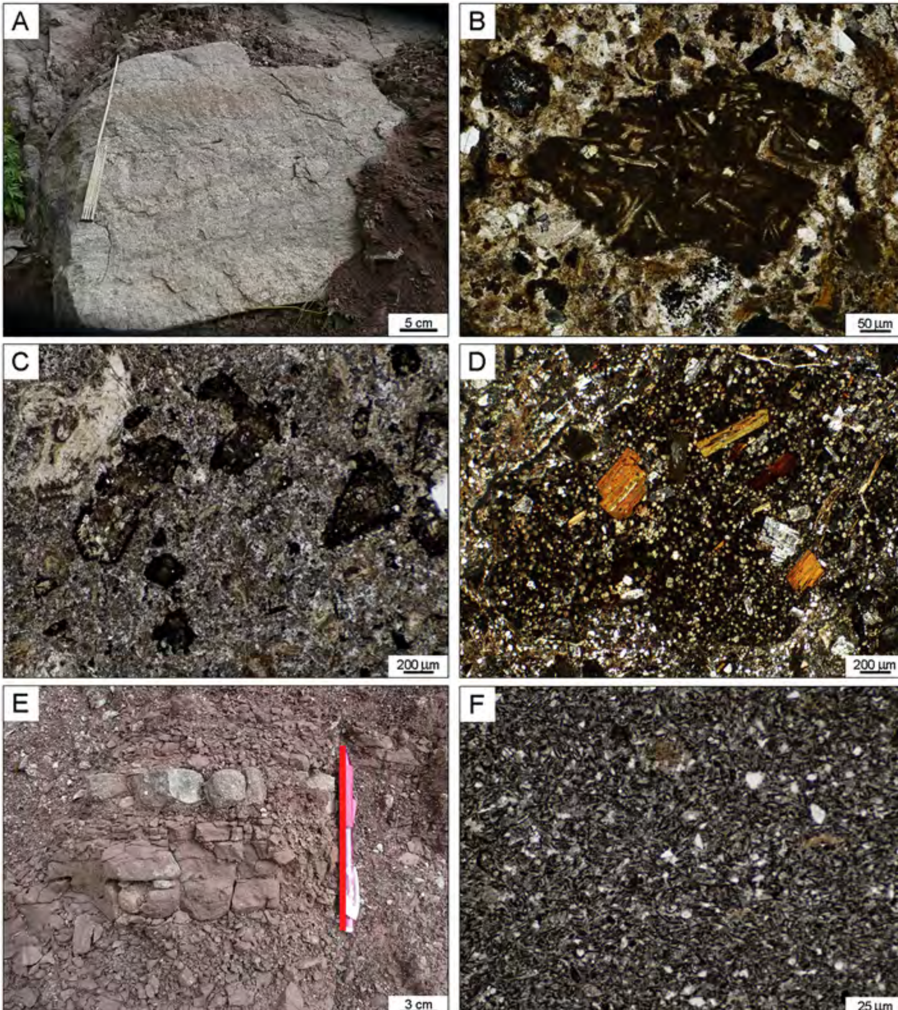


Figure 13

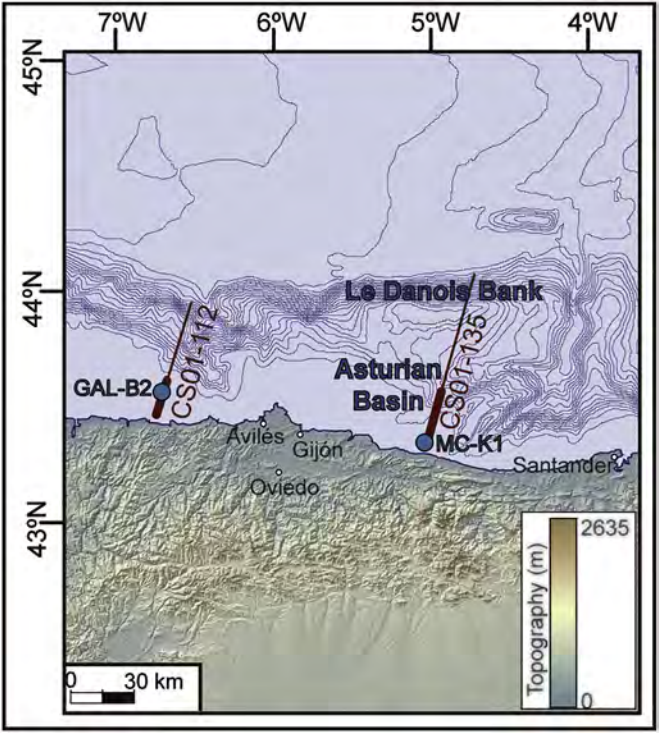
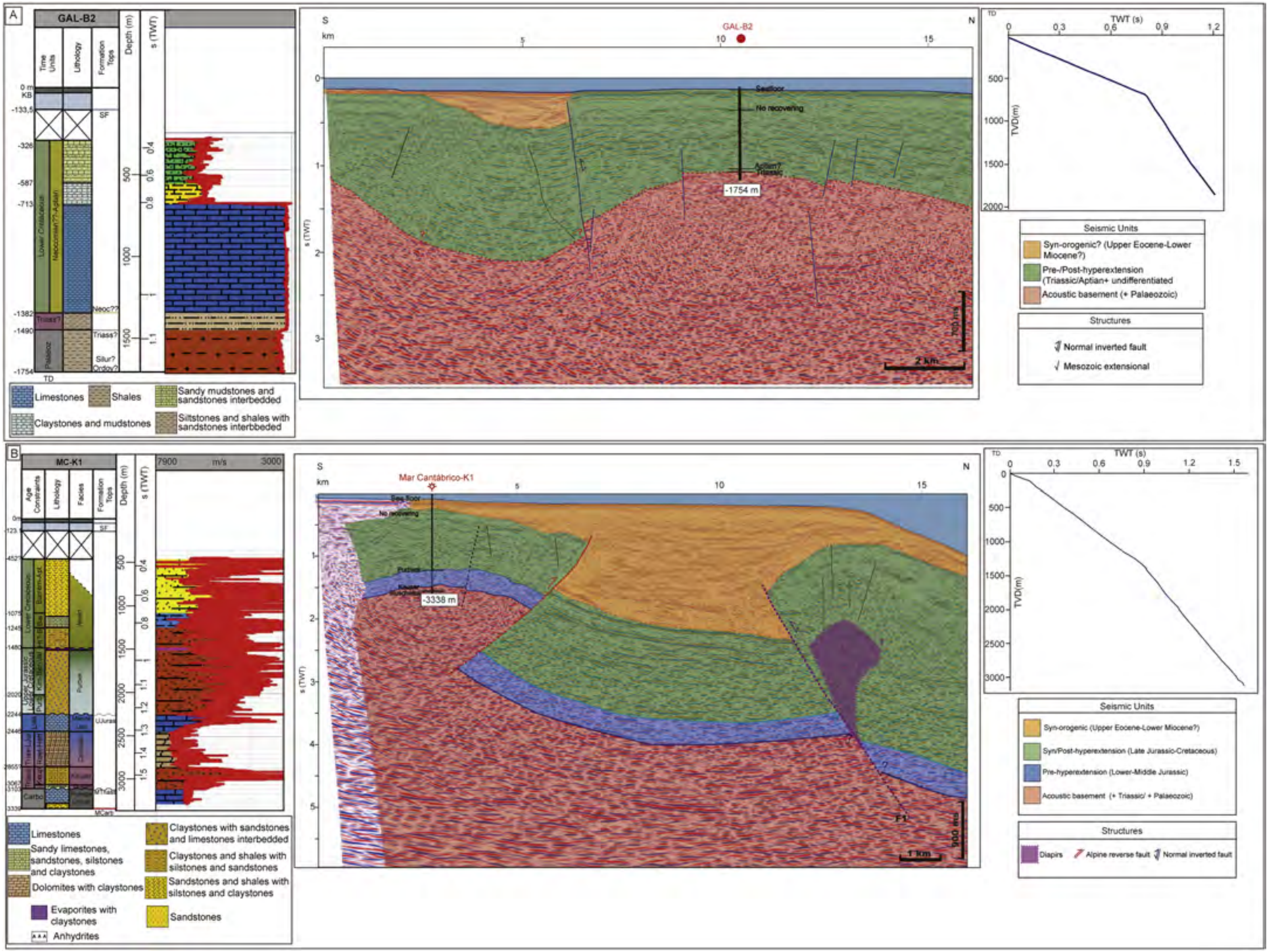
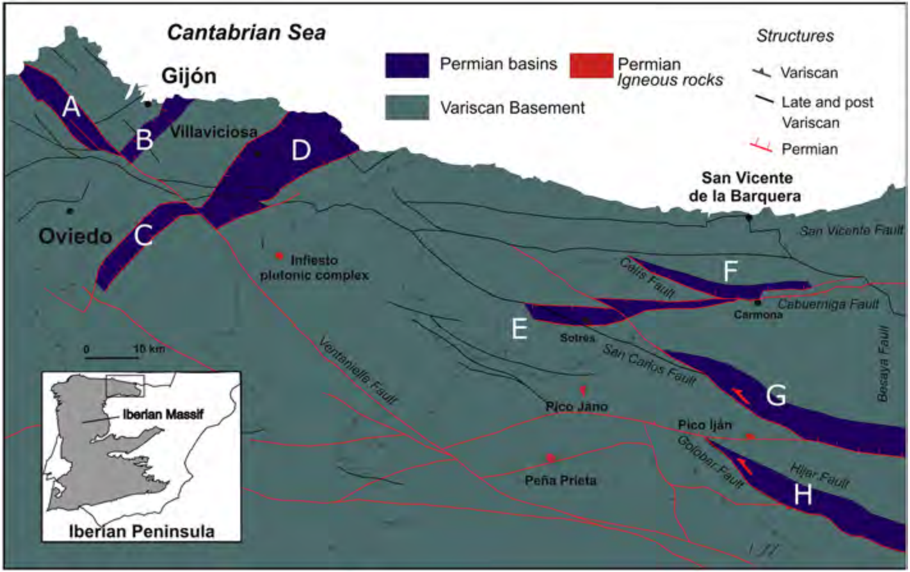

7ºW
6ºW
5ºW
4ºW
45ºN
44ºN
43ºN
Le Danois Bank
CS01-112
CS01-135
GAL-B2
Asturian
Basin
MC-K1
Avilés
Gijón
Oviedo
Santander
Topography (m)
2635
0
0
30 km

Figure 14



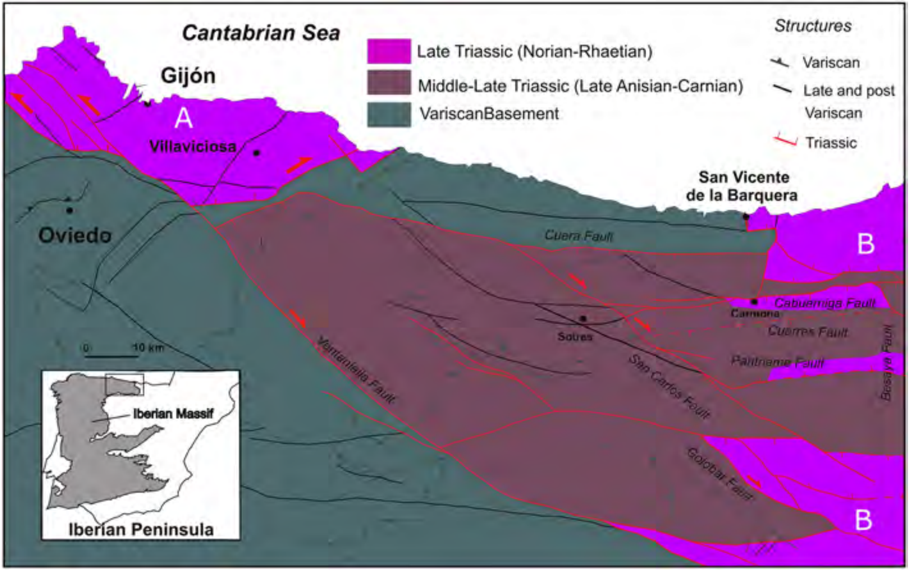
A
GAL-B2
Time Units
Lithology
Formation Tops
Depth (m)
s (TWT)
Lower Cretaceous
Neocomian?-Aptian
Triass?
Palaeoz
SF
Neoc??
Triass?
Silur? Ordov?
TD
Limestones
Shales
Sandy mudstones and sandstones interbedded
Claystones and mudstones
Siltstones and shales with sandstones interbbeded
S
N
km
GAL-B2
Seafloor
No recovering
Aptian?
Triassic
-1754 m
2 km
TWT (s)
TVD(m)
Seismic Units
Syn-orogenic? (Upper Eocene-Lower Miocene?)
Pre-/Post-hyperextension (Triassic/Aptian+ undifferentiated
Acoustic basement (+ Palaeozoic)
Structures
Normal inverted fault
Mesozoic extensional
B
MC-K1
Age Constraints
Lithology
Facies
Formation Tops
Depth (m)
s (TWT)
m/s
Limestones
Sandy limestones, sandstones, siltstones and claystones
Dolomites with claystones
Evaporites with claystones
Anhydrites
Claystones with sandstones and limestones interbedded
Claystones and shales with siltstones and sandstones
Sandstones and shales with siltstones and claystones
Sandstones
S
N
km
Mar Cantábrico-K1
Sea floor
No recovering
-3338 m
F1
1 km
TWT (s)
TVD(m)
Seismic Units
Syn-orogenic (Upper Eocene-Lower Miocene?)
Syn/Post-hyperextension (Late Jurassic-Cretaceous)
Pre-hyperextension (Lower-Middle Jurassic)
Acoustic basement (+ Triassic/ + Palaeozoic)
Structures
Diapirs
Alpine reverse fault
Normal inverted fault

Figure 15



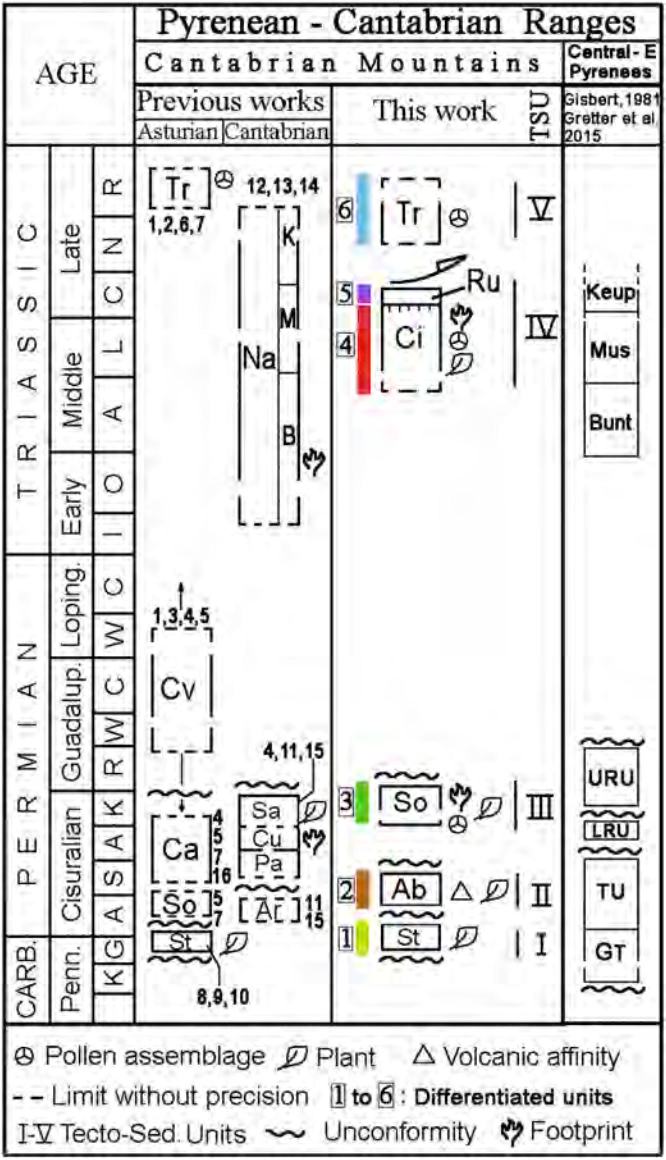
Cantabrian Sea
Gijón
Villaviciosa
Oviedo
A
B
C
D
E
F
G
H
Permian basins
Permian
Igneous rocks
Variscan Basement
Structures
Variscan
Late and post
Variscan
Permian
San Vicente
de la Barquera
San Vicente Fault
Infiesto
plutonic complex
Celis Fault
Cabuerniga Fault
Carmona
Sotres
San Carlos Fault
Besaya Fault
Ventaniella Fault
Pico Jano
Pico Iján
Golobar Fault
Hijar Fault
Peña Prieta
0
10 km
Iberian Massif
Iberian Peninsula

Figure 16



Cantabrian Sea
Late Triassic (Norian-Rhaetian)
Middle-Late Triassic (Late Anisian-Carnian)
VariscanBasement
Structures
Variscan
Late and post Variscan
Triassic
Gijón
A
Villaviciosa
Oviedo
San Vicente de la Barquera
B
Cuera Fault
Cabuerniga Fault
Carmona
Cuerres Fault
Polanco Fault
Besaya Fault
Sotres
San Carlos Fault
Ventaniella Fault
Golobar Fault
0 10 km
Iberian Massif
Iberian Peninsula

Figure 17



Pyrenean - Cantabrian Ranges
AGE
Cantabrian Mountains
Central - E Pyrenees
Previous works
Asturian
Cantabrian
This work
TSU
Gisbert,1981 Gretter et al 2015
TRIASSIC
PERMIAN
CARB.
Late
Middle
Early
Loping.
Guadalup.
Cisuralian
Penn.
R
N
C
L
A
O
I
C
W
C
W
R
K
A
S
A
G
K
Tr
1,2,6,7
12,13,14
K
M
Na
B
1,3,4,5
Cv
4,11,15
Sa
Cu
Pa
Ca
4
5
7
16
So
5
7
Ar
11
15
St
8,9,10
6
Tr
V
Ru
5
4
Ci
IV
3
So
III
2
Ab
II
1
St
I
Keup
Mus
Bunt
URU
LRU
TU
GT
Pollen assemblage
Plant
Volcanic affinity
- - Limit without precision
1 to 6 : Differentiated units
I-V Tecto-Sed. Units
Unconformity
Footprint

Figure 18