ISSN (print): 1698-6180. ISSN (online): 1886-7995
www.ucm.es/info/estratig/journal.htm

Journal of Iberian Geology 37 (2) 2011: 103-120
doi: 10.5209/rev_JIGE.2011.v37.n2.1

Journal of Iberian Geology
AN INTERNATIONAL PUBLICATION OF EARTH SCIENCES

Geometry, structures and evolution of the western termination of the Alpine-Pyrenean Orogen reliefs (NW Iberian Peninsula)

Geometría, estructuras y evolución de la terminación occidental de los relieves del Orógeno Alpino-Pirenaico (NO Península Ibérica)

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Received: 15/01/11 / Accepted: 29/07/11

Abstract

The geometry, structures and tectonic evolution of the western termination of the Alpine-Pyrenean Orogen relief onshore and related foreland have been studied. We present the results of structural mapping and detailed outcrop studies of Cenozoic-age structures carried out at the NW Iberian Peninsula. On the basis of this work we propose a new tectonic model for the termination. According to the identified structures, three main regions could be recognised: (1) the Astur-Galaica (AG) region or the western part of the Cantabrian Mountains (CM), characterised by thrusts with a south vergence, which are the continuation of the structures of the Pyrenees, (2) The Galaico-Leoneses Mountains (GLM), characterized by thrusts with a north vergence, and (3) The Rías Baixas-Terra Chá region (RBT) characterized by strike-slip faults with no relevant associated relief but with recent seismic activity, which represents the less deformed Alpine foreland. The western termination of the Alpine-Pyrenean Orogen is formed due to the superposition of two mountain ranges (CM and GLM) and a complex tectonic evolution. The CM were emplaced southwards and subsequently the GLM was emplaced northwards. The western limit of the E-W thrusts of the CM and the associated relief define a N-S-oriented arch-shape structures (Ibias-Ancares and Rúa-Vilalba). Tectonic activity commenced during the Eocene, and in the westernmost areas during the Late Oligocene. The CM south-verging thrust activity ended at the beginning of Late Miocene, although deformation continued in the GLM with north-verging thrusts. The evidence of intense tectonic activity during the Miocene, the western migration and southward transference of tectonic activity and the interaction of two successive deformation fronts, suggests that a re-examination of the tectonic evolution of the northern Iberian microplate during the Alpine Orogeny is necessary.

Keywords: NW Iberian Peninsula, Cantabrian Mountains, lateral orogen termination, deformation transference, Alpine-Himalayan Orogen

Resumen

Se han estudiado las estructuras, la geometría y la evolución tectónica de la terminación occidental de los relieves del Orógeno Alpino-Pirenaico (o Cántabro Pirenaicos) y del antepaís asociado. Se presentan los resultados de la cartografía estructural y estudios detallados de campo de las estructuras tectónicas cenozoicas del NO de la Península Ibérica. Basándose en este estudio proponemos un nuevo modelo tectónico para esta terminación. En función de las estructuras tectónicas identificadas se han diferenciado tres regiones: (1) la Astur-Galaica que es la terminación más occidental de la Cordillera Cantábrica (CC) y que se caracteriza por cabalgamientos con vergencia sur y por ser la continuación natural de las estructuras que configuran el Pirineo. (2) Los Montes Galaico-Leoneses (MGL) que se caracteriza por cabalgamientos con vergencia norte. Finalmente, (3) la región de las Rías Bajas-Terra Cha que se caracteriza por fallas de desgarre con sismicidad asociada que no generan relieve importante y que representan el antepaís menos deformado. La terminación del Orógeno Alpino-Pirenaico es el resultado de la superposición de dos cadenas montañosas: la Cordillera Cantábrica (CC) que es prolongación de los Pirineos y los Montes Galaico Leoneses (MGL), con una compleja evolución tectónica. La CC se emplazó hacia el sur y posteriormente fueron los MGL los que se emplazaron hacia el norte. El límite occidental de los cabalgamientos de dirección E-O que elevan la CC son dos estructuras arqueadas de dirección N-S (Ibias-Ancares y Rúa-Vilalba). La actividad tectónica comenzó durante el Eoceno y en las zonas más occidentales es durante el Oligoceno. La actividad de los cabalgamientos de la CC finalizó al principio del Mioceno superior. Mientras tanto, la deformación continuó en los cabalgamientos de los MGL que se emplazaban hacia el norte. Las evidencias de intensa actividad tectónica durante el Mioceno, la migración hacia el oeste y la transferencia de la deformación hacia el sur, así como la interacción de dos frentes de deformación sucesivos, sugiere una revisión de la evolución tectónica del norte de la microplaca Ibérica durante la Orogenia Alpina.

Palabras clave: NO Península Ibérica, Cordillera Cantábrica, transferencia de la deformación, terminación lateral de orógenos, Orogeno Alpino-Himalayo

1. Introduction

The Alpine-Himalayan Orogen has its westernmost expression onshore in the Iberian Peninsula, the Alpine-Pyrenean orogen in the north (or Pyrenean-Cantabrian) and the Betic Chains in the south (Fig. 1A) (Dewey 1977). These orogenic belts resulted from the collision of the Iberian Plate and the Eurasian and African Plates, respectively. The Alpine-Pyrenean orogen (the Pyrenees and the Cantabrian Mountains (CM)) (Fig. 1B) formed due to the oblique convergence and collision between the microcontinent Iberia and Eurasia from Late Cretaceous until Early Miocene times (Dewey *et al.*, 1989; Srivastava *et al.*, 1990; Muñoz, 1992; Jabaloy *et al.*, 2002; Andeweg, 2002). Geologically speaking, their common origin and cartographic continuity would suggest that these mountain ranges are part of a continuous orogen whith reliefs extend 800 km in an E-W trend (Choukroune *et al.* 1990; Pulgar *et al.* 1996; Teixell, 1998; Muñoz, 2002; Gallastegui *et al.*, 2002; Barnolas and Pujalte, 2004). The western part of the Alpine-Pyrenean orogen reliefs is called the Cantabrian Mountains. In Galicia the main reliefs of the Cantabrian Mountains ends just before the Atlantic Ocean, except for the Xistral Mountains (1,000 m height) a narrow range located north of this region (Fig. 1C). Tectonic structures continue westward until the Mid-Atlantic Ridge but offshore (e.g., As Pontes Fault, in Fig. 2).

Precambrian to the Cenozoic-age sediments were affected by the Alpine Orogeny (Fig. 1B), although, the sedimentary varies considerably along an east-west transect. In the eastern part of the orogen, there is a good Mesozoic pretectonic sedimentary record, and a complete record of the Cenozoic syntectonic succession is preserved in the Ebro, Duero and Aquitaine basins. However, in the westernmost part, where the Pyrenean Orogen takes place over the Variscan basement (Iberian Massif) the lack of Mesozoic rocks and the scarcity of Cenozoic sediments (Fig. 1B) make it very difficult to recognize the Alpine tectonics (Martín-Serrano *et al.*, 1996). Moreover, existing models for the eastern part of Cantabrian Mountains and Pyrenees are not applicable in the westernmost regions (Alonso and Pulgar, 2004). This complex tectonic evolution is partly due to the result of the superposition of two orthogonal orogenic events: the Variscan and the Alpine orogenies (Gallastegi *et al.*, 2002), but also due the fact that this region represents the lateral termination of this reliefs. Finally, due to the intense basement deformation, it is difficult to recognize the presence and nature of post-Variscan structures, which in many cases resulted from reactivation processes taking place on paleozoic structures.

The relief of the Alpine Orogeny in northern and northeastern Iberian Peninsula, trends east-west with a constant width of around 80 km in the Pyrenees and eastern Cantabrian Mountains. However, in the northwestern part, the Alpine relief changes direction (southwards) and separates into a series of individual mountain ranges with peaks above 2,000 m (e.g. Teleno Ranges, Segundera Ranges, etc), which can be grouped in the Galaico-Leoneses Mountains that increase the orogen width more than 200 km (Fig. 1C). These mountains determine the sharp end of the Duero basin towards the west (Fig. 1B).

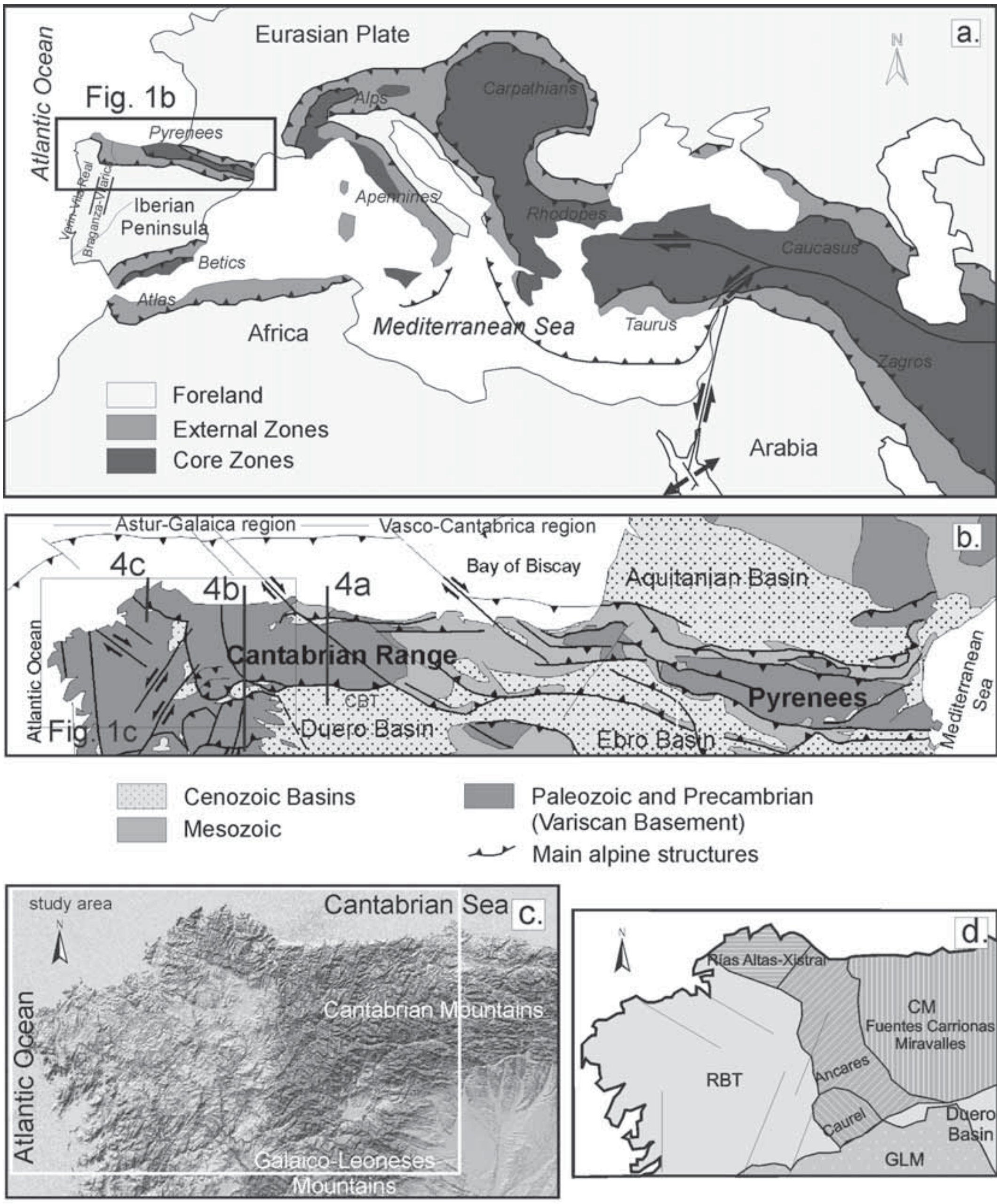

Fig. 1.- A: Generalized map of the western segment of the Alpine-Himalayan Orogen and location of the study area (modified from Dewey 1977 and Twiss and Moores, 1992). B: Generalized map of the Alpine-Pyrenean Orogen with the tectonic division proposed. CBT= Cantabrian Basal Thrust. C: Shaded relief map of the NW Iberian Peninsula (SRTM 90 m). D: Sketch showing the three main regions and sectors proposed for the NW Iberian Peninsula.

Fig. 1.- A. Mapa general del segmento occidental del Orógeno Alpino-Himalayo y la localización de la zona de estudio (modificado de Dewey 1977 y Twiss y Moores, 1992). B. Esquema geológico del Orógeno alpino Pirenaico con la división tectónica propuesta. CBT= Cabalgamiento Basal Cantábrico. C. Mapa sombreado de relieve del NO de la Península Ibérica (SRTM 90m). D. Esquema mostrando las tres principales regiones y sectores propuestos para el NO de la Península Ibérica.

The Cantabrian Mountains, with a height of up to 2,600 m and an E-W trend end in a flat region with heights lower than 500 m, named Terra Cha (Fig. 1C).

The study of the Alpine relief along the NW Iberian Peninsula has implications for the evolution of the Alpine Orogeny and the Iberian microcontinent geodynamics. In addition, this region was considered a seismically stable area, due to its location on ancient basement far from the seismic plate boundaries. However, the unexpected seismic activity (Lugo seismic crisis in 1995 and 1997) has increased the interest of seismotectonic studies in this area (De Vicente and Vegas, 2009). These studies have revealed the need to better understand the Cenozoic structures and clarify existing models, in order to explain the seismic activity in this region. These structures are still a subject of debate (González-Casado and Giner, 2000; Rueda and Mezcua, 2001; López-Fernández *et al.*, 2004; Martín-González, *et al.*, 2006; Martínez-Díaz *et al.*, 2006; Martín-González, 2009) and despite the interest and implications of this termination, the geometry, structures and Alpine evolution are poorly defined and detailed mapping of these is required (Martín-Serrano *et al.*, 1996; Alonso and Pulgar, 2004; Barnolas and Pujalte, 2004; Martín-González, 2009).

The purpose of this paper is to identify, characterize, and map the Alpine structures of the NW Iberian Peninsula (based on the results of structural mapping, field surveying and detailed outcrop studies) with special emphasis in this western termination, in order to propose both a tectonic subdivision and a tectonic model that might explain the major elements (geological and geomorphological features) of these areas. These elements are outlined in figures 1B, 1C, and 3 and include:

-The abrupt end of the main E-W trending relief of the Cantabrian Mountains.

-The widening to the south of the Alpine relief.

-The structures that control limits and sedimentation in the Tertiary depressions, as well as, the distribution and dissection of the Tertiary sediments, that appear in two main trends: E-W (El Bierzo and O Barco depressions) and N-S (Sarria, Monforte and Vilalba depressions)

-The relationship between the conspicuous fault corridors of the NW Iberian Peninsula (Braganza-Vilariça and Verín-Vila Real) and all the structures of the Cantabrian Mountains (CM).

2. Geological setting

The NW Iberian Peninsula predominantly comprises Precambrian and Paleozoic lithologies (Fig. 1 B). These rocks were mainly deformed during the Carboniferous in the Variscan Orogeny which are intruded by igneous rocks, mainly in the western region, during the Carboniferous and Permian. The overall Variscan structure shows an arch-like shape (Asturian Arch) open to the west, where the inner parts of the Varsican Orogen are located (Martínez Catalán *et al.*,1990; Arenas and Martínez Catalán, 2003).

The Alpine-Pyrenean Orogen is composed of the Pyrenees in the east and the Cantabrian Mountains in the west (Gallastegui *et al.*, 2002; Muñoz, 2002; Barnolas and Pujalte, 2004). The Pyrenees form the border between Eurasia and the Iberian Peninsula, trend ESE-WNW and represent a doubly vergent continental collision orogen (Choukroune *et al.*, 1990; Munoz, 1992; Teixell, 1998). The double vergence is asymmetric with the south Pyrenean Zone (southward vergence) being wider that the north Pyrenean Zone (northward vergence). Two continental foreland basins: the Ebro Basin in the south and Aquitaine basin in the north, formed as a result of this double vergence.

The structures of the south Pyrenean Zone continue westward across the Cantabrian Mountains, while the structures of the north Pyrenean Zone continue offshore into the Cantabrian Sea (Cámara, 1997; Gallastegui *et al.*, 2002). Similarly, the continuation of the Ebro foreland Basin is the Duero Basin, while the Aquitaine Basin continues westward into the Landes Plateau and the Bay of Biscay abyssal plain.

The Alpine structures of the Cantabrian Mountains can be divided, based on lithology, age and deformational style of their rocks, into two regions: the Vasco-Cantabrica (VC) in the E and the Astur-Galaica (AG) in the W (Figs. 2 and 1B)

The Vasco-Cantábrica region is characterized by a thick and complete succesion of Mesozoic sediments (Triassic to Cretaceous). In the north, the extensional Mesozoic structures were partially inverted during the Alpine compressional regime (Espina, 1994; Pulgar *et al.*, 1996) whole, in the south, the Mesozoic succession appears to be detached.

The Astur-Galaica region is characterized by the absence or rarity (only in the eastern part outcrops a thin and fairly complete sequence) of Mesozoic sediments. Cenozoic sediments are found in small isolated depressions. In the eastern part of this region, the thin Mesozoic cover is undetached and deformed in a thick-skin tectonic style. In this region, the overall structure (Fig. 4A) is a regional monoclinal flexure that corresponds to the back-limb of a major fault-bend fold related to the Cantabrian Basal Thrust (CBT) (Alonso *et al.*, 1996). This north-dipping basement thrust overturn the Mesozoic-Cenozoic sediments in the south border of the Cantabrian Mountains.

However, the tectonic model is not well defined for the westernmost part, where the Orogen relief ends, (Martín-Serrano *et al.*, 1996, Alonso and Pulgar, 2004). Until today, the study of Alpine tectonics in this region is mainly based on the structure of the Tertiary depression, with tectonic interpretations still a subject of debate. An example of this controversy can de found in the El Bierzo, Quiroga and O Barco basins, where E-W normal faults have been proposed to control the basin evolution (Sluiter and Pannekoek, 1964; Herail, 1981; González Lodeiro *et al.*, 1982) or NE-SW for the Lemos and Sarria basins (Vergnolle, 1985; Santanach, 1994). Although,

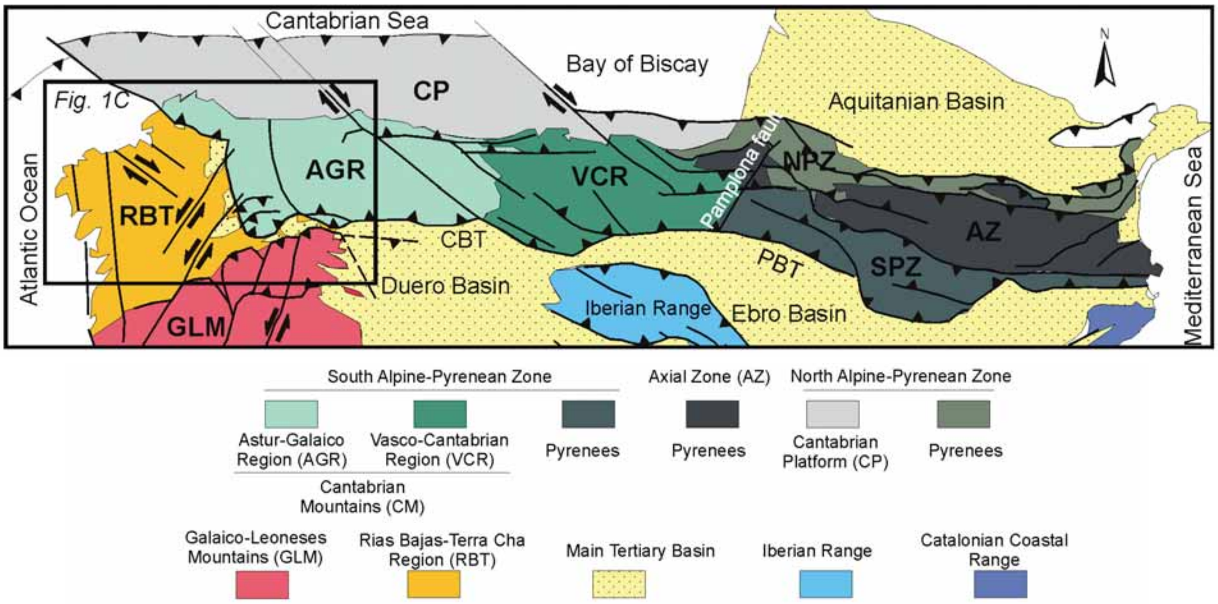

Fig. 2.- Structural sketch showing the different region of the Alpine-Pyrenean Orogen and north of Iberian Peninsula (See text for explanation).

Fig. 2.- Esquema estructural mostrando las diferentes regiones del Orógeno Alpino Pirenaico y del Norte de la Península Ibérica (ver texto para explicación).

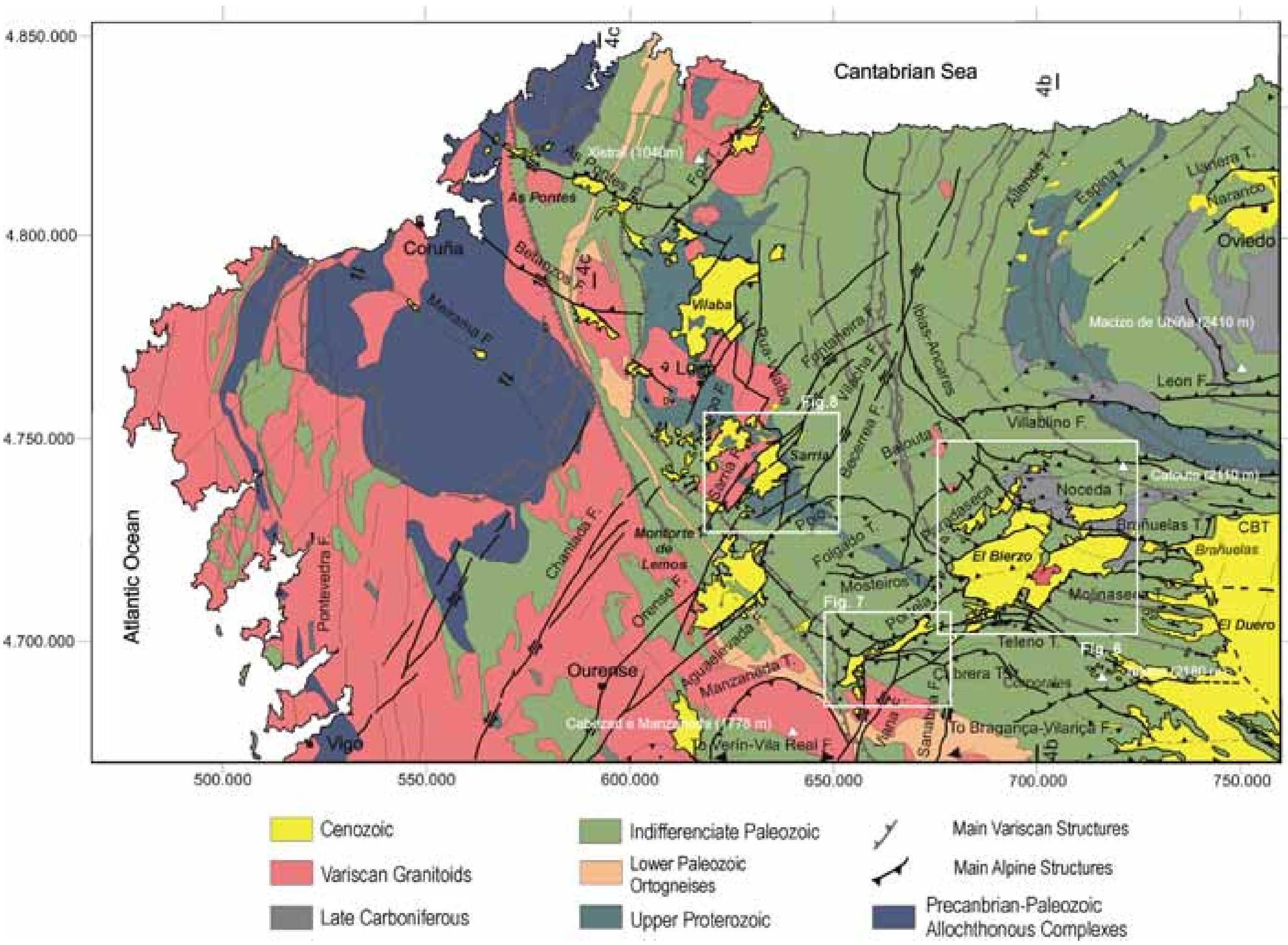

Fig. 3.- Structural map of the NW Iberian Peninsula. Major Alpine and Variscan structures have been mapped.

Fig. 3.- Mapa estructural del NO de la Península Ibérica. Principales estructuras alpinas y variscos han sido representadas.

some authors have suggested E-W thrusts instead of normal faults (Vergnolle, 1990; Santanach, 1994; Heredia *et al.*, 2004; Martín-González, 2009). Finally, other authors have proposed that NE-SW strike-slip faults and restraining bends are the main control (Olmo, 1985; Barrera *et al.*, 1989; Yepes and Vidal Romaní, 2003; Heredia *et al.*, 2004; De Vicente and Vegas, 2009).

The general tectonic model proposed (Santanach, 1994; Cabrera *et al.*, 1996; Vegas *et al.*, 2004; Santanach *et al.*, 1988, 2005; De Vicente and Vegas, 2009) for the termination of the Alpine-Pyrenean orogen, suggest that the shortening along the CBT was transferred south across the NE-SW left lateral corridors of Bragança-Vilariça and Vila Real-Verín. To the west of this transfer zone, residual convergence is partially accommodated by NW-SE right lateral faults. According to this model, the NE-SW corridors limits the Duero Basin to the west and generates the El Bierzo and O Barco depressions and the Sarria and Monforte as intramontane basins in the hinterland (see for details Santanach, (1994)). De Vicente and Vegas (2009) emphasize the importance of the reorientation of the CBT to the NE-SW corridors in order to explain the change in topography and the intraplate deformation of the NW Iberian Peninsula.

Despite the difficulty of dating Tertiary continental sediments in the NW Iberian Peninsula (Martín Serrano *et al.*, 1996), the age of the northern As Pontes, Bierzo and Oviedo-Infiesto have been dated by fossils. The ages are Oligocene to Early Miocene in As Pontes Basin (López Martínez *et al.*, 1993; Santisteban *et al.*, 1996; Alonso *et al.*, 1996; Santanach *et al.*, 2005); and Late Eocene in the Oviedo Basin (Truyols *et al.*, 1991). Recently, a latest Early Oligocene age has been established for the El Bierzo depression (Freudenthal *et al.*, 2010).

3. Methods

The identification of the Alpine structures in the NW Iberian Peninsula was based on structural mapping, field surveying and detailed outcrop study of the identified faults. Due to the geographical scale of the Alpine deformational style, the cartographic scale chosen was 1:200,000 for the entire mapped area. In addition, 1:50,000 and 1:25,000 cartographic scales were chosen for detailed mapping in key areas such as the Tertiary-age depressions and intersecting set of structures. The Variscan structures were compiled from IGME maps (1:200,000 and 1:50,000 scale). The characteristics of the NW Iberian Peninsula have focused the structural mapping on the conspicuous Variscan structures, but in some cases neglecting the Alpine structures in this region (e.g. Téna-Dávila, and Capdevilla, 1975). All previous Alpine structural maps in these regions were compiled (e.g. Santanach, 1994; Martín Serrano 1994; Alonso *et al.*, 1996; Martín-González, 2009, De Vicente and Vegas, 2009). However, there are conspicuous gaps in structural data especially in the Galaico-Leoneses Mountains, the Rias Baixas-Terra Cha Region and in the westernmost Cantabrian Mountains. In these areas we carried out detailed structural mapping (1:25,000 and 1:50,000), as well as a revision of the available geological maps (1:50,000 and 1:200,000). In places where no Tertiary sediments allowed for the identification of Alpine activity, we have assessed this on the basis of analysis of geomorphic markers, such as erosion surfaces, river network patterns, position of mountain fronts, etc. (Martín-González, 2009). In the study area, a widespread planation surface has been dissected and displaced due to subsequent Cenozoic tectonics and, therefore, it can be used as a marker to measure vertical displacements (García-Abad and Martín-Serrano, 1980; Martín-González, 2009). In order to evaluate these vertical displacements on the erosion surface, longitudinal elevation profiles over SRTM DEMs have been carried out (90 m spatial resolution).

4. Structures of the western termination of the Alpine-Pyrenean Orogen reliefs

According to the present study, the western termination of the Alpine Orogen reliefs onshore and its related foreland can be subdivided in three regions based on structural and morphological characteristics (Fig. 2 and 1D). Astur-Galaica region (AG) (the westernmost part of the Cantabrian Mountains), the Galaico-Leoneses Mountains (GLM) and, in the west, the Rías Baixas-Terra Chá region (RBT). The AG is characterized by thrusts with a south vergence, the GLM is characterised by thrusts with a north vergence, while the RBT is characterized by NE-SW and NW-SE trending faults mainly reactivated as strike-slip faults during the Alpine compression, but without significant associated reliefs. In the RBT Mesozoic N-S normal faults are also observed near the Atlantic Coast, but Alpine reactivation is not recorded apparently.

4.1.The Astur-Galaica region

The western Astur-Galaica region (Figs. 1B and 2) is bounded to the south by an imbricate thrust system that forms the continuation of the Cantabrian Basal Thrust (CBT) (Figs. 2 and 1 B). These thrusts superimpose the Cantabrian Mountains on the Duero Basin and, in the west, on the El Bierzo and O Barco depressions (Fig. 3).

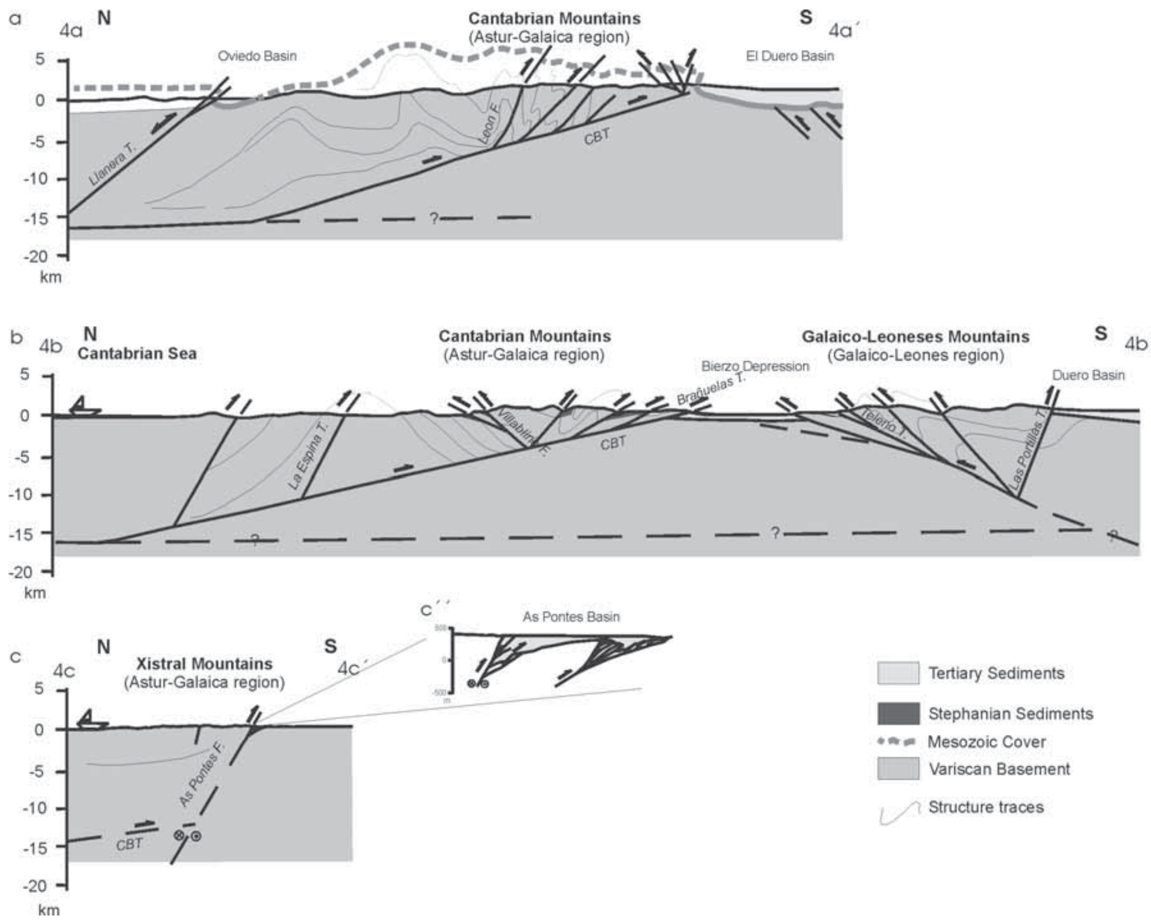

Fig. 4.- Three N-S cross sections of the western part of the Alpine-Pyrenean Orogen relief. Location in Fig. 1b and 3. A: N-S cross section through the Cantabrian Mountains showing the south verging Cantabrian Basal Thrust (CBT) over the Duero basin. Mesozoic cover is deformed and used as a marker (modified from Alonso *et al.*, 1996) B: N-S cross section through the Cantabrian Mountains and Galaico-Leoneses Mountains. C: N-S cross section through the Xistral Mountains (CM) (c'': detailed cross section of the As Pontes basin, modified from Santanach *et al.*, 2005).

Fig. 4.- Tres cortes N-S del la parte más occidental de los relieves alpinos del Orogeno Pirenaico. Se encuentran localizados en las figuras 1b y 3. A. corte N-S por la Cordillera Cantábrica mostrando la vergencia sur del Cabalgamiento Basal Cantábrico (CBT) sobre la cuenca de El Duero (Modificado de Alonso *et al.*, 1996). B. Corte N-S por la Cordillera Cantábrica y los Montes Galaico Leoneses. C. Corte N-S por la Sierra de Xistral (CC) (c'' corte de detalle a través de la cuenca de As Pontes, Modificado de Santanach *et al.*, 2005).

The western limit is the structure Vilallba-A Rúa fault zone, that trends N-S and links up with the As Pontes Fault. As Pontes is a NW-SE right lateral strike-slip fault with an important reverse component, uplifting the northern block.

Differences in orientation, kinematics and morphological expression of the Alpine structures support the division of this region into four sectors: Fuentes Carrionas-Miravalles, Ancares, Caurel and Rías Altas-Xistral (Figs. 2 and 1D).

Fuentes Carrionas-Miravalles sector

This sector (Fig. 1D) is the largest of the Astur-Galaica region and is bounded on the east by the Vasco-Cantábrica region and by Ibias-Ancares fault zone in the west. In the study area (western part) is characterized by a sequence of thrusts affecting the Late Carboniferous (Stephanian) and Tertiary sediments of the El Bierzo Basin (Figs. 3, 4B, and 6). These imbricate thrusts dissect the Tertiary basin and have a mainly south vergence (e.g. Tombrio and Noceda thrusts) (Figs. 5a and 5b). Backthrusts in the north slope of this sector are common (e.g. Villablino and Sabero-Gordon thrusts, Figs. 4A and 4B), and result in the formation of tectonic pop-up that uplifts the highest peaks of the western Cantabrian Mountains (Catoute-Nevadin peak, 2,100 m) (Fig. 3). In the eastern part of this sector, where the Variscan arch-like shape structure is oriented E-W (Fig. 3), Reactivation of Variscan thrust faults and a squeezing of Variscan folds is also noted (Alonso *et al.*, 1996). However, in the western part of this sector, the Alpine structures offset the Variscan structures and only E-W structures, related to Late Carboniferous basins, are reactivated (Figs. 5B and 5C).

The Alpine deformation in this sector is concentrated along the southern border, while deformation in the rest of this sector is less concentrated. Imbricate thrusts are present only along the northern border of the Oviedo-Infiesto Tertiary basin. The other Alpine-age structures are reverse faults, originally steeply-dipping Variscan thrusts, which were reactivated in the northern flank of the Variscan arch. These faults have a NE-SW orientation and determine the deposit of Tertiary sediments and its deformation (e.g. Espina and Allande thrusts, Fig. 3) (De Vicente *et al.*, 2007). Towards the south, where these structures turn to a N-S orientation, they are not reactivated.

The Fuentes Carrionas-Miravalles sector merges westward with the Ibias-Ancares structure. The Ibias-Ancares structure is a complex steeply-dipping fault zone that was already active during the Late Carboniferous (Pulgar *et al.*, 1981; Bastida *et al.*, 1980). The curved and anastomosed trace follows Variscan trends (Fig. 3). Therefore, as a result of the Alpine N-S horizontal compression, the northern segment of this structure is reactivated as a right lateral strike-slip fault, while to the south it is transformed into an imbricate thrust system (e.g. Brañuelas thrusts).

Ancares sector

The Ancares sector is located to the west of the Ibias-Ancares structure (Fig. 1D). Its deformation is concentrated along the southern margin within an imbricate thrust system, thrusting the northern El Bierzo depression (Figs. 3 and 4). The number of structures and the overall shortening in this sector are less than in the Fuentes Carrionas-Miravalles sector. These structures deformed and dissect the Tertiary basins of el Bierzo and O Barco (Figs. 6 and 7). In this sector the orientation of the Alpine structures are NE-SW (e.g. Paradaseca and Rubiana thrusts) (Figs. 5E, 5F, and 9A) presenting a left lateral component. The change in orientation may be related to a change in orientation of the old basement structures (Asturian Arch), which run NW-SE in this sector (Fig. 3). As in the Fuentes Carrionas-Miravalles sector, backthrusts (e.g. Balouta) generate a tectonic pop-up where the highest peaks (2,000 m) are located (Martín-González, 2009).

The Rúa-Vilalba and Ibias Ancares structures partially transfer the CBT deformation to the north (Fig. 4C). So, the Rúa-Vilalba structure can be considered a lateral ramp and a transpressive structure of the CBT. The NE-SW strike-slip faults, offset the structure and dissect the related Tertiary foreland sediments, obliterating its cartographic continuity (Fig. 3). Thus, the western border of Ancares sector is the Rúa-Vilalba structure that terminates the E-W sequence of imbricate thrusts (e.g. La Portela thrust) (Fig. 3). This structure is also the western limit of the Cantabrian Mountains and only a pre-Cenozoic planation surface (500 m), dissected by the recent rivers, can be identified to the west: The Rias Baixas-Terra Cha region, the less-deformed foreland (Figs. 1C, 1D ,and 2). The trace of the Rúa-Vilalba structure is sub-parallel to the Ibias-Ancares structure. The Rúa-Vilalba structure has a vertical component that uplifts the eastern block and superimposes basement onto the Tertiary-age Monforte, Sarria (Fig. 8) and Vilalba depressions (Figs. 5D, 9B, and 9C).

El Caurel sector

The El Caurel sector (Fig. 1D) is separated from the Ancares sector by the Valcarce River and the Poio Thrust (Fig. 3). The El Caurel sector is characterized by a series of NE-SW thrusts with a NNW vergence (Fig. 3) which are responsible of the uplift of the NE-SW elongated Caurel Mountains (1,600 m). These thrusts (e.g. Folgado and Poio Thrusts) have an arched geometry with slip surfaces dipping from 22º to 70º and linking up with the structures from the southern Galaico-Leoneses Mountains region that cut the Cantabrian Mountains front (Fig. 3). Thus, several structures from the Ancares sector (E-W and NW-SE) of the Cantabrian Mountains are offset by these NE-SW thrusts with NNW vergence (e.g., Mosteiros and Villafranca thrusts). The geometry of the rivers and thrusts in this sector is quite parallel to the thrust fronts and its slope and the associated reliefs increases towards the SSE: this can be interpreted as a footwall block and lateral thrust propagation sequence (Martín-González, 2009).

Rías Altas-Xistral sector

The Rías Altas-Xistral (Fig. 1D), a narrow area with a relief close to 1,000 m in height (Xistral Mountains), is the westernmost sector of the Alpine-Pyrenean Orogen reliefs (Figs. 3 and 4C). Structures in this sector show evidences of little shortening. This sector is limited by the As Pontes and Foz faults. The As Pontes Fault is a right lateral strike-slip fault trending NW-SE (Santanach *et al.*, 1988, 2005). It is parallel and has the same kinematics as the Meirama and Betanzos faults (Fig. 3). In contrast, the As Pontes Fault has a relevant vertical component that uplifts the northern block. These faults superimpose basement onto Tertiary sediments (e.g., the As Pontes and Roupar faults) (Santanach *et al.*,1988, 2005).

4.2. Galaico-Leoneses Mountains region

The Galaico-Leoneses Mountains (GLM) (Fig. 2) are bounded to the north by an imbricate thrust system with a northern vergence, that also forms the southern border

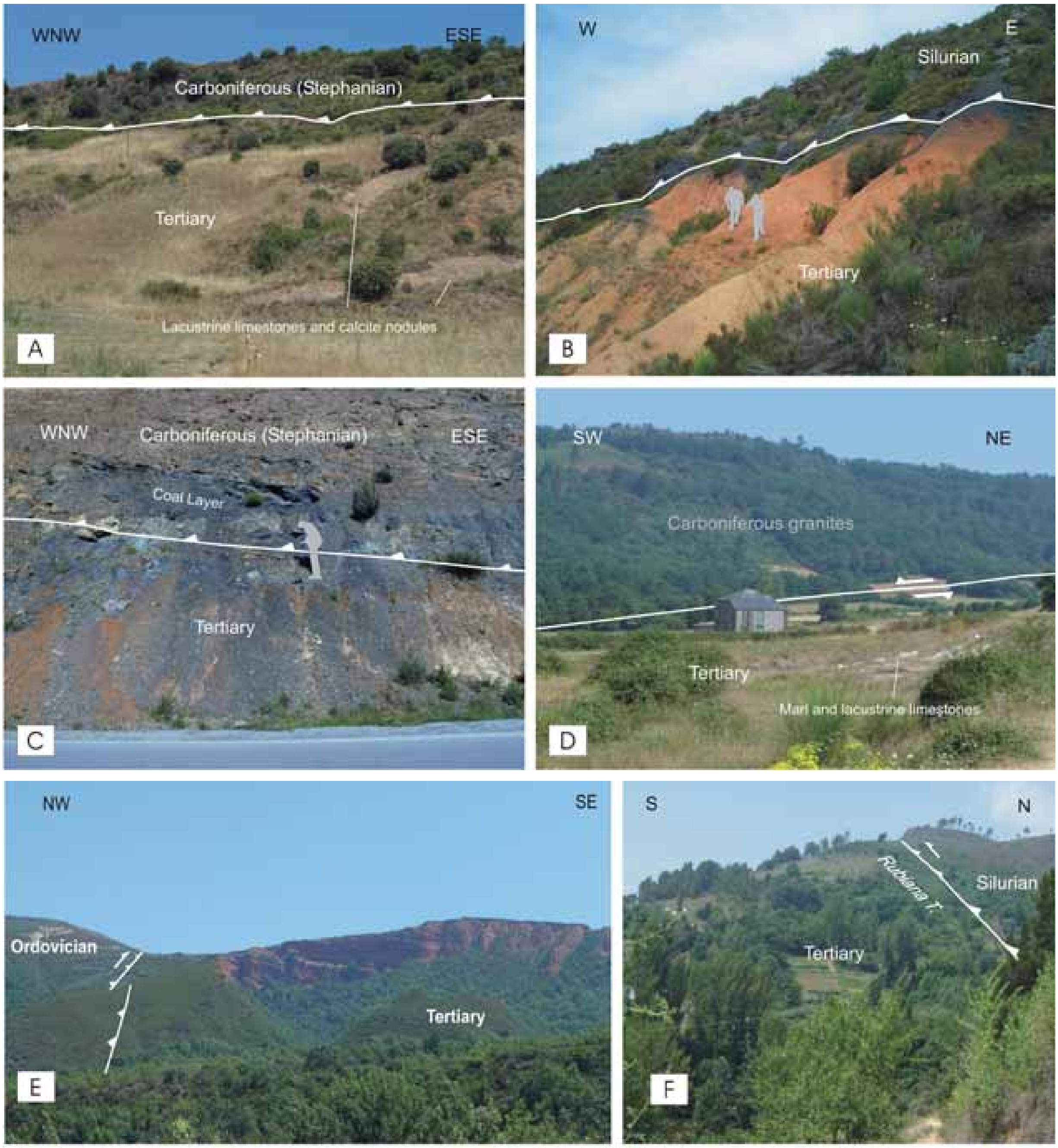

Fig. 5.- Field examples of Alpine structures. A: The Tombrio thrust at the north of the El Bierzo depression (Carboniferous sandstones, conglomerates and coal over Tertiary sands, clays, and lacustrine limestones and marls –Toral Fm). B: The Noceda thrust at Villar de las Traviesas (Silurian slates over Tertiary sands and clays). C: The Brañuelas thrust at the northern border of the El Bierzo depression (at Rodanillo) (Carboniferous sandstones, conglomerates, and coal beds over Tertiary sands and clays- Toral Fm). Note that the thrust is detached along the coal layer). D: Lancara fault at the northern border of the Sarria depression (Carboniferous granites over Tertiary clay, marl and lacustrine limestone- Toral Fm). E: The Paradaseca thrust at Leitosa Médulas (Ordovician quartzite and slates, over tertiary sands, gravels, pebbles, and boulders). Note the progressive unconformity in the Tertiary sediments caused by the southward emplacement of the Paradaseaca thrust. F: The Rubiana thrust, north of the O Barco depression (Silurian quartzite and slates over Tertiary sands and clays).

Fig. 5.- Ejemplos de campo de estructuras alpinas. A. Cabalgamiento de Tombrio en el norte de la depresión de El Bierzo (areniscas, conglomerados y carbón sobre arenas, arcillas, calizas y margas lacustres de la Fm Toral). B. El cabalgamiento de Noceda en Villar de las Traviesas (pizarras silúricas sobre arenas y arcillas terciarias). C. Cabalgamiento de Brañuelas en el borde norte de la depresión de El Bierzo (Rodanillo) (areniscas, conglomerados y capas de carbón del Carbonífero sobre arenas y arcillas de la Fm Toral). Nótese que el cabalgamiento se produce a favor de una capa de carbón. D. Falla de Lancara en el borde norte de la depresión de Sarriá (granito carbonífero sobre arcillas, margas y calizas lacustres de la Fm Toral). E. Cabalgamiento de Paradaseca en las Médulas de la Leitosa (cuarcitas y pizarras ordovícas sobre arenas, gravas y bloques terciarios). Nótese la discordancia progresiva en los sedimentos terciarios causada por el emplazamiento hacia el sur del cabalgamiento. F. El cabalgamiento de Rubiana, norte de la depresión de O Barco (cuarcitas y pizarras silúricas sobre arenas y arcillas terciarias).

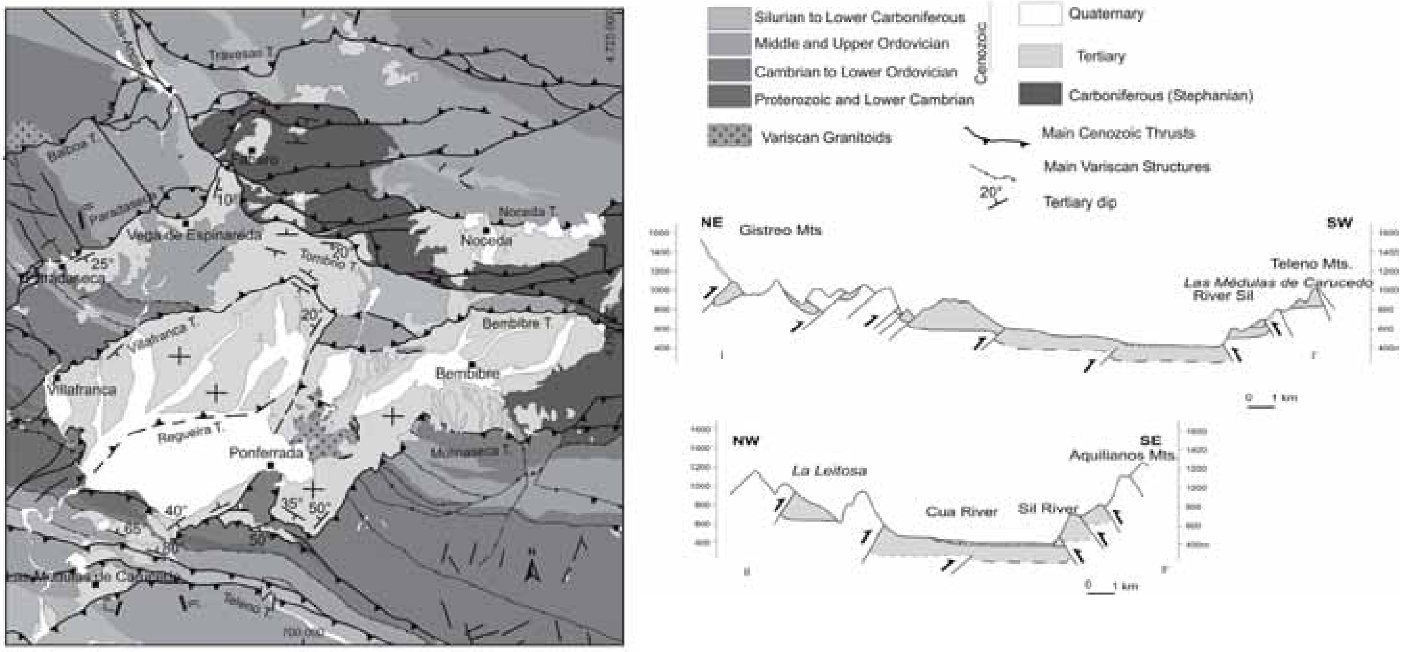

Fig. 6.- Detailed geological map and cross sections of the El Bierzo Tertiary depression. Location in figure 4. Tertiary sediments are limited and dissected mainly by south and north verging thrusts showing a tectonic pop-down.

Fig. 6.- Mapa geológico de detalle y cortes de la depresión terciaria de El Bierzo. Localización en figura 4. Los sedimentos terciarios están limitados y segmentados principalmente por cabalgamientos vergentes tanto al norte como al sur, mostrando una tectónica de tipo *pop-down*.

of the Tertiary deposits of the El Bierzo and O Barco depressions (Figs. 6, 7, and 9D). These depressions are also bounded in the north by the CBT, which generated a tectonic pop-down where the sediments are preserved (Fig. 9A). The north-vergent thrusts of the GLM dissect the previously emplaced thrusts of the Cantabrian Mountains front, and raise the northern part of the ancient Duero foreland basin, individualizing the El Bierzo and O Barco Tertiary depressions (Fig. 3). The other Alpine structures in the GLM are strike-slip faults, in many cases related to the thrust, conforming their lateral structures. The NE-SW-trending faults are mainly left lateral strike-slip faults (e.g. Viana and Sanabria faults) and are linked with the NE-SW corridors of the Iberian Massif (Braganza-Vilariça and Vila Real-Verín) (Fig. 3). The highest peaks of this region, such as Teleno (2,100 m) and Cabeza de Manzaneda (1,700 m), are located in the north, close to the main alpine thrusts (Figs. 3 and 4).

4.3. Rías Baixas-Terra Chá region

The Rías Baixas-Terra Chá region (Fig. 2) has few topographic contrasts, and is mainly characterized by a pre-Cenozoic planation surface of 400-500 m (García Abad and Martín Serrano, 1980; Martín-González, 2009). In this region Tertiary-age sediments, mainly surrounding the Cantabrian and Galaico-Leoneses Mountains, are preserved. The region represents the western less-deformed foreland of the Alpine-Pyrenean orogen. The characteristic structures of this region are NE-SW left-lateral strike-slip faults (e.g. Orense and Chantada faults), NW-SE right-lateral strike-slip faults (e.g. Meirama and Betanzos faults) and N-S steeply dipping faults (e.g. Pontevedra fault). These faults produce the fragmentation of the remaining foreland basin, located near of the lateral end of the Cantabrian Mountains, which is displaced by these faults (Fig. 3), individualizing the Monforte, Sarria and Vilalba depressions (Martín-González y Heredia, 2011).

NE-SW trending strike-slip faults are widespread across the NW Iberian Peninsula, with displacements being mainly horizontal with no outstanding associated relief, (except close to the El Caurel sector, where they show a reverse component, e.g. Fontaneira and Sarria faults) (Fig. 5D). Vertical displacement can be up to 300 m (Becerreá fault) and generating pivotal and hinge faults, which control the Tertiary depressions (e.g Monforte and Sarria). This tectonic interpretation agrees with the gravimetric studies of the Sarria depression, where it has been shown that the basin depocentre geometry is controlled by NE-SW faults (Martín-González *et al.*, 2003). A vertical component is also recognized in the NE-SW faults in Portugal which were reactivated in Upper Miocene-Quaternary times (Cabral, 1989; Carvalho *et al.*, 2006). The NE-SW faults are associated with active seismicity (González-Casado and Giner, 2000; Rueda and Mezcua, 2001; López-Fernández *et al.*, 2004; Martínez-Díaz *et al.*, 2006) and this together with observed reorganisation of drainage (Martín-González, 2009), would suggest a significant Late Miocene-Quaternary-age activity along these faults.

The NE-SW strike-slip faults can be subdivided into two groups: N 40º-60º and N 20º-30º. The first group is widespread in the NW Iberian Peninsula and has the same orientation as a series of regional diabase dykes (Abril and Rodríguez-Fernández, 1981), and fractures related to opening of the Atlantic Ocean during Late Jurassic and Early Cretaceous times (Ancochea *et al.*, 1992, Vegas *et al.*, 2004). Moreover, the N 40º-60º orientation and kinematics are consistent with an E-W-oriented extension. Therefore, we consider this fault group to be mainly Mesozoic in age with fault reactivation associated with the N-S Alpine compression. Taking into account that the horizontal maximum compression calculated in the area is SSE-NNW (Herraiz *et al.*, 2000; González-Casado and Giner, 2000), it is likely that the NE-SW strike slip faults were reactivated in the Alpine compressional regime. The second group is more consistent with a N-S Alpine compression and has hydrothermal and seismic activity associate (e.g. Orense Fault).

The N-S steeply-dipping faults are located mainly along the Atlantic coast (e.g. Pontevedra Fault). These faults are related to Mesozoic extension related with the opening of the Atlantic Ocean (Boillot and Malod, 1988). The N-S faults are offset by NE-SW and NW-SE strike slips faults (Fig. 3).

5. Tertiary sediments and Alpine tectonics

The aforementioned structures, mapped in the western extension of the Alpine-Pyrenean Orogen, have been developed mainly in a Paleozoic basement which was highly deformed during the Variscan Orogeny, with scarce overlain of Tertiary sediments. These sediments are found in isolated outcrops and tectonic depressions mainly filled by terrigenous continental sediments, transported by alluvial fans under arid or semi-arid conditions as a response to tectonic activity (Alonso *et al.*, 1996; Alonso Gavilán *et al.*, 2004). The sedimentary synorogenic record is similar in the main basins and three formations have been identified. From base to top these are the: Toral, Santalla and Médulas formations (Herail, 1981; Martín-González and Heredia, 2011). The Toral Fm is mainly composed of clay, lacustrine limestones and arkosic sandstones (Fig. 5A and 9E). The Santalla Fm comprises sandstones, gravels and polygenetic pebbles (quartzite, shales, sandstone and mudstone clasts) and lutites. The Médulas Fm is composed of gravels

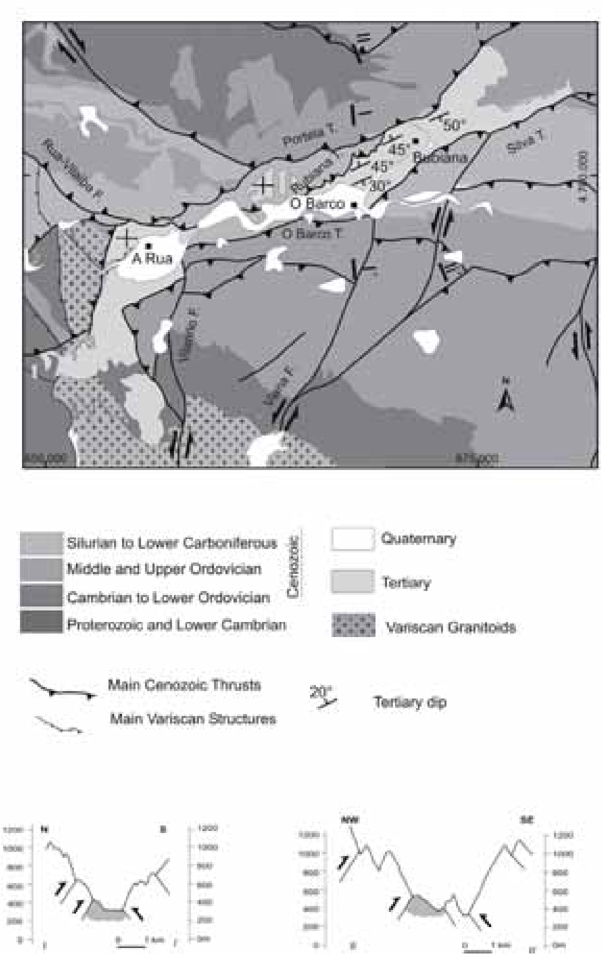

Fig. 7.- Detailed geological map and cross sections of the O Barco Tertiary depression. Location in Figura 4. Tertiary sediments are limited and dissected mainly by south and north verging thrusts showing a tectonic pop-down. Note the relation of north verging thrusts with the NE-SW strike slip faults and the turn northward of the Portela thrust (CBT).

Fig. 7.- Mapa geológico de detalle y corte de la depresión terciaria de O Barco. Localización en figura 4. Los sedimentos terciarios están limitados y segmentados principalmente por cabalgamientos vergentes tanto al norte como al sur, mostrando una tectónica de tipo *pop-down*. Nótese la relación de los cabalgamientos vergentes al norte con los desgarres NE-SW y el giro hacia el norte del cabalgamiento de la Portela (parte del Cabalgamiento Basal Cantábrico)

(including pebbles and boulders of quartzite) sandstones and rare lutites. The Médulas Fm overlies the basement while the other tertiary formations lies uncorformably to disconformably towards their distal parts.

The Paleocurrents observed (Herail, 1981; Pagés *et al.*, 2001; Martín-González and Heredia, 2011), suggest that the lower formation (Toral Fm) has a source area located to north and west, in the Cantabrian Mountains. This formation is always dissected and deformed by the mapped Alpine structures (Fig. 5A and 5B). In contrast, the Santalla Fm shows north and south provenances. The coarse clast sizes suggests an increase in tectonic activity

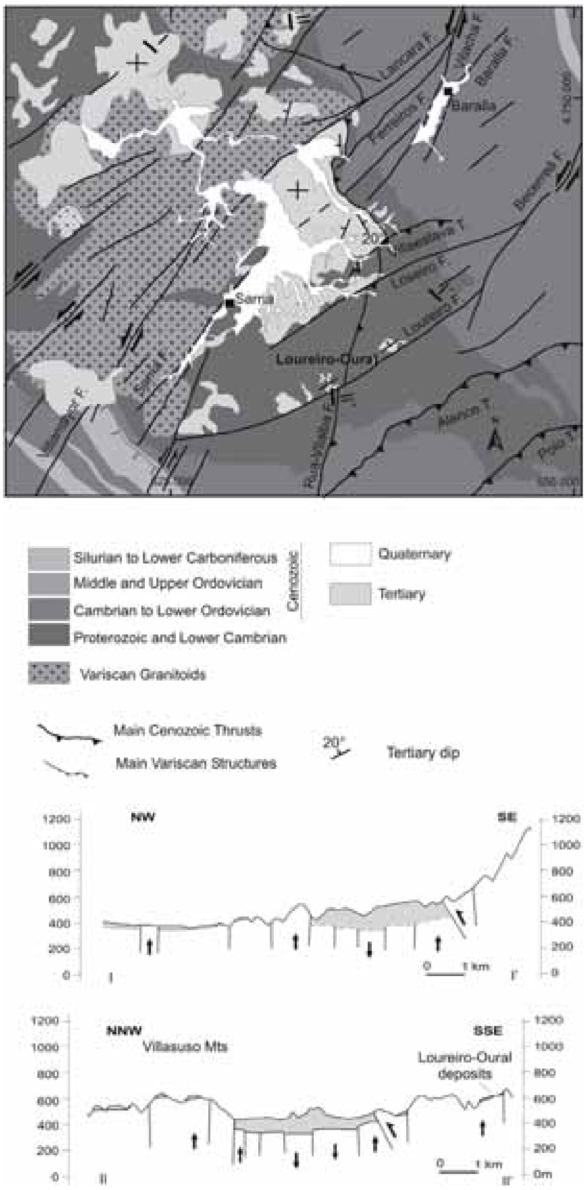

Fig. 8.- Detailed geological map and cross sections of the Sarria Tertiary depression. Location in Figure 4. Tertiary sediments are limited and dissected mainly by NE-SW strike-slip faults with a vertical component and eastward by a N-S structure (Rua-Vilalba). Note the offset and displacement of the N-S structure by the strike-slip faults.

Fig. 8.- Mapa geológico de detalle y corte de la depresión terciaria de Sarria. Localización en figura 4. Los sedimentos terciarios están limitados y segmentados principalmente por desgarres NE-SW con componente vertical y por el este por una estructura N-S (Rúa-Vilalba). Nótese el desplazamiento de la estructura N-S por los desgarres.

and a closer orogenic front, related to the reliefs located north and south (Cantabrian and Galaico-Leoneses Mountains) (Fig. 5E). The Médulas Fm sediments indicate a south provenance related to the present-day relief and tectonic activity of the Galaico-Leoneses Mountains, indicating the final phase of intramontane basin evolution.

The structural and sedimentary data suggest that the present-day Tertiary depressions are the remains of a more extensive foreland basin that was subject to compartmentalization in its final stages. Moreover, border facies related to the faulted boundaries of this initial foreland basin have not been found (Martín-González and Heredia, 2011).

The paleontological data of the Toral Fm indicate a Oligocene to Early Miocene age in As Pontes Basin (López Martínez *et al.*, 1993; Santanach *et al.*, 2005), Early Oligocene in the El Bierzo (Freudenthal *et al.*, 2010) and Late Eocene in the Oviedo Basin (Truyols *et al.*, 1991).

6. Discussion

Based on detailed structural mapping and observations as presented herein, we propose a new model for the western termination of the Alpine-Pyrenean Orogen. This model connects with the currently accepted models for the eastern Cantabrian Mountains (Alonso *et al.*, 1996; Pulgar *et al.*, 1999; Gallastegui *et al.*, 2002). In that part of the Cantabrian Mountains the main structure consists of a regional monoclinal flexure of a major fault-bend fold of the Cantabrian Basal Thrust- CBT (Fig. 4A). Toward the west, the CBT emerges as an imbricate thrust system verging southwards (e.g. Brañuelas and Noceda thrusts) (Fig. 3 and 4) and the monoclinal flexure is transformed into a tectonic pop-up (Ancares and El Caurel Mountains, 2,000 m) due to a series of backthrusts (e.g. Villablino Thrust) (Fig. 4B).

No data from Alpine structures at upper crustal scales are available in the westernmost termination. Therefore, we have followed crustal constraints used by other authors in the eastern part of the studied area (Alonso *et al.*, 1996; Pulgar *et al.*, 1996; Gallastegui *et al.*, 2002) (Fig. 4). These thrust, and the associated relief, decrease displacement westward and finally they link up with N-S-orientated arch-shaped structures (called Ibias-Ancares and Rúa-Vilalba). The Rúa-Vilalba structure, is a large fault zone that partially transfers the terminal CBT shortening to the north into the As Pontes Fault (Fig. 3 and 4C). The Rúa-Vilalba and Ibias-Ancares structures are the western limit for the Cantabrian Mountains (Fig. 3 and 10). Additionally the Rúa-Vilalba structure is the eastern boundary of the Tertiary-age Monforte, Sarria and Vilalba depressions. These Tertiary depressions also trend N-S, parallel to the Rúa-Vilalba structure. These lateral structures can be correlated with the western end of a high velocity intracrustal layer, which has been interpreted as the indented lower crustal wedge emplaced during the crustal thickening of the Alpine-Pyrenean

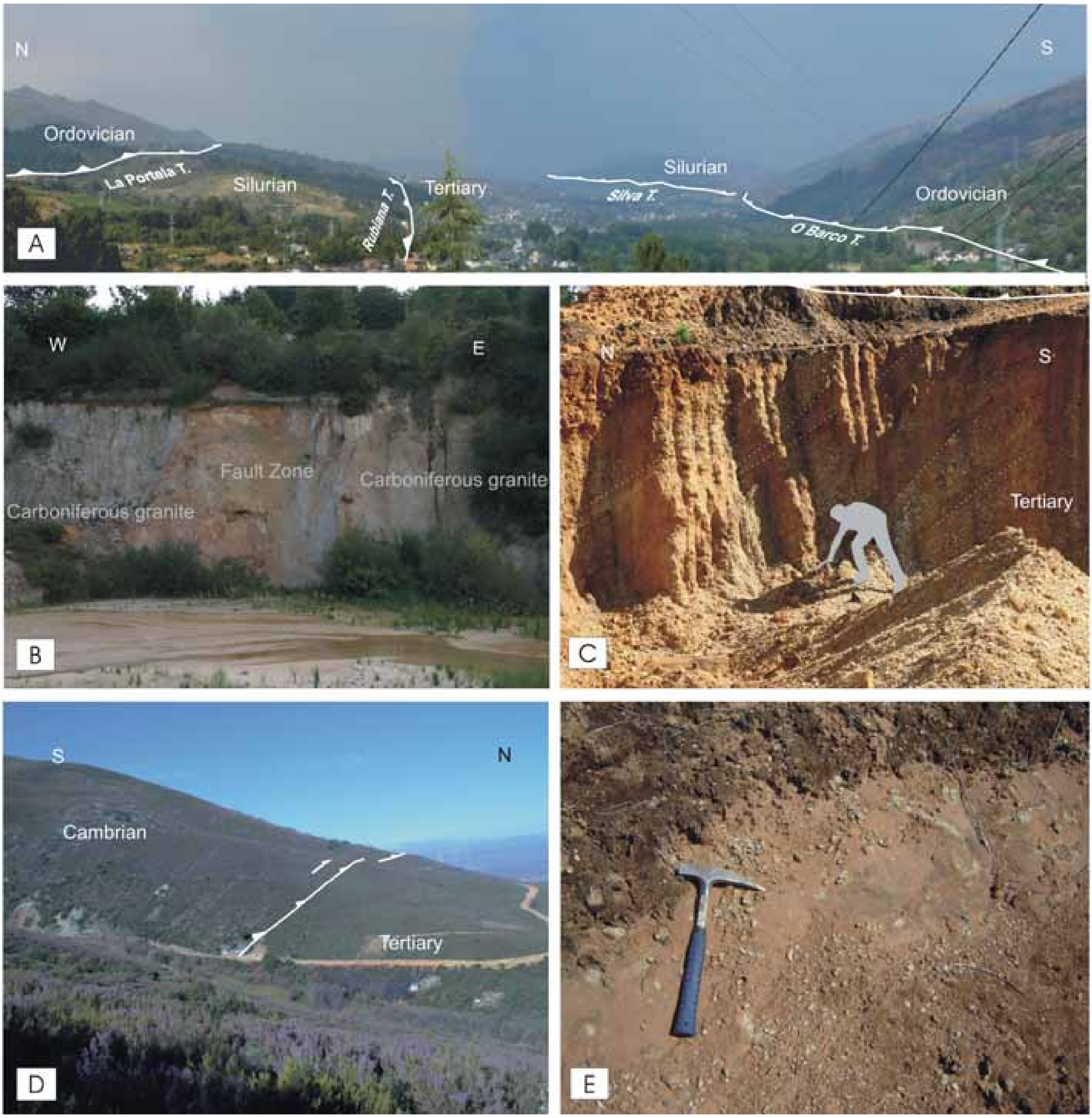

Fig. 9.- Field examples of Alpine structures and tertiary sediments. A: O Barco tectonic pop-down, in which the tertiary sediments were preserved. The Cantabrian Mountains (Astur-Galaica region), uplifted by north-vergent thrusts, are in the left part of the picture. The Galaico-Leoneses Mountains, uplifted by north-vergent thrusts, are in the right part of the picture. B: The Rúa-Vilalba structure showing a wide band of brittle deformation in a granite (Castroverde granite) C: Tertiary deposits (sands, gravels and pebbles and boulders) at the eastern border of Vilalba depression. Deformed by the Rua-Vilalba structure. D: The Molinaseca thrust at the south border of the El Bierzo depression (Cambrian quartzite and slates over Tertiary sand and gravels) in Bembibre. E: Tertiary claystone (Toral Fm) in the El Bierzo depression showing bioturbation.

Fig. 9.- Ejemplos de campo de estructuras alpinas y sedimentos terciarios. A. *Pop-down* tectónico de O Barco, dentro del cual están preservados los sedimentos terciarios. La Cordillera Cantábrica (Region Astur-Galaica), elevada por los cabalgamientos vergentes hacia el norte está en la parte izquierda de la fotografía. Los Montes Galaico-Leoneses, elevados por los cabalgamientos vergentes hacia el sur, se encuentran en la parte derecha de la fotografía. B. La estructura de Rúa Vilalba mostrando una amplia banda de deformación frágil sobre un granito (granito de Castroverde). C. Depósitos terciarios (arenas, gravas y bloques) en el borde oriental de la depresión de Vilalba, deformados por la estructura de Rúa-Vilalba. D. Cabalgamiento de Molinaseca en el borde sur de la depresión de El Bierzo (Cuarcitas y pizarras sobre gravas y arenas terciarias) en Bembibre. E. Limolitas y arcillas de la Fm Toral en la depresión de El Bierzo mostrando bioturbación.

Orogen (Pedreira *et al.*, 2007). One explanation for the westernmost lateral end of this seismic and gravimetric high velocity layer may be the Ibias-Ancares and Rúa-Vilalba structures, which form the western end for the Cantabrian Mountains.

Subsequently, the emplacement of north-verging thrusts resulted in uplift of the Galaico Leonese Mountains (Teleno and Cabrera peaks, 2,100 m) and displacement of the Cantabrian Mountains structures (e.g. Villafranca and Portela thrusts). Thus, these north-vergent thrusts and related NE-SW faults, generate an E-W tectonic pop-down (Fig. 7), segment the ancient Tertiary foreland basin (e.g. El Bierzo and O Barco depressions) and also divided the El Caurel sector from the Ancares sector (Fig. 3 and 10).This activity produced the vertical displacement of the Tertiary deposits (Fig. 6). The most relevant vertical displacement is recorded in Corporales (Teleno Mountains) where Tertiary sediments from the El Bierzo depressionwere uplifted a minimum of 900 m. Crosscutting relationships are in agreement with the apatite fission track studies that show how the Galaico-Leoneses Mountains begin the uplift after the Cantabrian Mountains (Miocene vs Oligocene) (Martín-González *et al.*, 2008).

The paleocurrents and lithologies indicate, for the earlier stages, a distal position to the northern thrusts (CM). Meanwhile, intermediate and final stages indicate north and south provenance related with the present relief. Moreover, no fault border facies have been found in the earlier stages. Therefore, only after the emplacement of the GLM thrusts, would the El Bierzo and O Barco depressions be considered as intramontane basins. The basin evolution, proposed in this work, is similar to described in the Central Andes, where the foreland basin of the east verging main Andes (Alta Cordillera and Precordillera) is deformed and dissected by the uplift of the foreland basement of west-verging Sierras Pampeanas mountains (Rodríguez Fernández *et al.*, 1999; Ramos *et al.*, 2002). This type of foreland basins is called "Broken Foreland Basin" by Jordan (1995).

The shortening of the GLM north verging thrusts is compensated by the NE-SW left-lateral strike-slip faults in the west, and the right-lateral strike-slip faults in the east (Fig. 3). The kinematics and arch shape of El Caurel indicate a N and NNW tectonic transport. NE-SW oriented strike-slip faults are widely distributed on the NW Iberian Peninsula. These faults displace and in some sectors obliterate the Rúa-Vilalba structure. Their displacements are mainly horizontal with no relevant associated relief, except where they run near the El Caurel sector where they show a vertical component that generates pivot and hinge faults. The horizontal component is responsible for the dissection of the Tertiary-age sediments in the Monforte, Sarria and Vilalba depressions (Fig. 8). Vertical component is also recognized in the NE-SW trending faults in Portugal which were reactivated in Upper Miocene-Quaternary times (Cabral, 1989; Carvalho *et al.*, 2006)).

The geological map of the figure 3 shows that the thrust trace of the Cantabrian Mountains turns northward, decrease displacement and the final displacement is partially transferred in this direction by N-S lateral structures (Ibias Ancares and Rúa-Vilalba) (Fig. 3, 6 and 8). In this way, the continuation of the CBT is not along the NE-SW left lateral corridors of Braganza-Vilariça and Vila Real-Verín (Santanach, 1994; Vegas *et al.*, 2004; De Vicente and Vegas, 2009). The model described by these authors does not explain the significant relief of the Galaico-Leoneses Mountains (up to 2,100 m) and the tectono-sedimentary evolution of the NW Tertiary depressions (El Bierzo, Sarria, Monforte). However, in the present model the Galaico-Leoneses Mountains are uplifted by the north vergent thrusts (Fig. 7). The proposed model agrees with the activity of these strike-slip corridors during the southward emplacement of the Cantabrian Mountains, this tectonic style is well known where thrust belts turn or curve, producing large strike-slip corridors into the foreland, as is the case in the Himalayas (e.g. Molnar and Taponier, 1975; Shen *et al.*, 2001; Storti *et al.*, 2003). But these corridors are not the main responsible for the Galaico Leoneses-Mountain uplift that take place later (Fig. 10).

The Variscan basement features of the NW Iberian Peninsula make difficult to date the Cenozoic tectonic activity (Martín-Serrano *et al.*, 1996). However, in the light of the present work and the newly published paleontological ages, we can establish some restrictions with regards to the timing of the Alpine tectonic activity. The paleontological ages for the Toral Fm are Late Oligocene to Early Miocene in As Pontes (López Martínez *et al.*, 1993; Santanach *et al.*, 2005), Lower Oligocene in el Bierzo (Freudenthal *et al.*, 2010) and Late Eocene in Oviedo (Truyols *et al.*, 1991). On the other hand, the GLM were active during the time of deposition of Santalla Fm. This formation can be correlated with Candanedo Fm (Duero Basin), whitch is Oligocene in age (Colmenero, 1982; Corrochano, 1989) and can extend up into Upper Miocene times (Vallesian) (Herrero *et al.*, 2004). The Oligocene age for the Toral Fm is coeval with that of the As Pontes age (Fig. 10). These observations suggest that tectonic activity began in the northeast (Oviedo-Infiesto Basin) during the Eocene and migrated

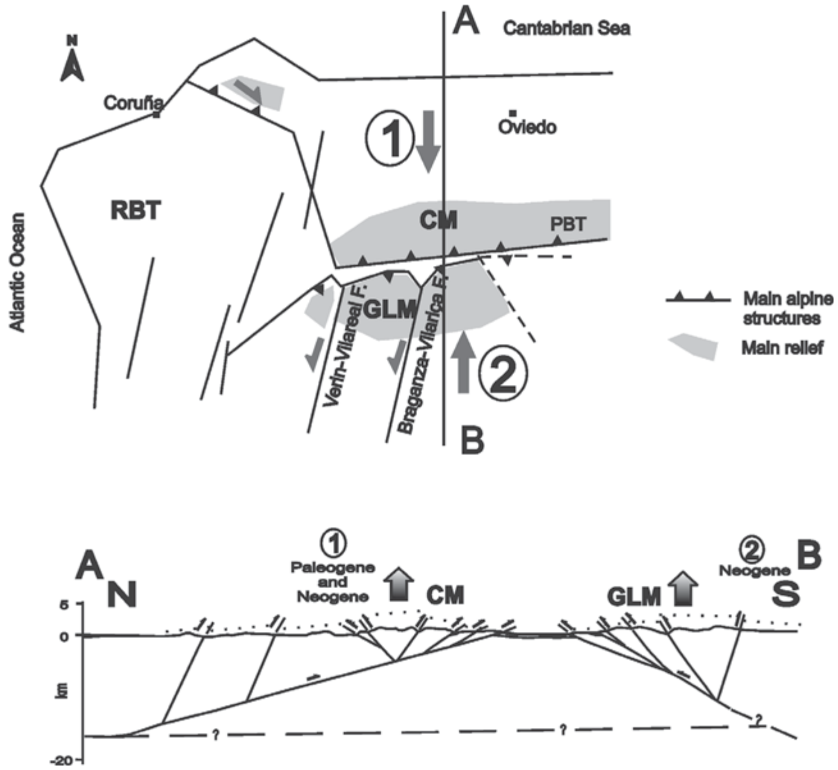

Fig. 10. - Tectonic sketch map and cross section showing tectonic model proposed of the western termination of the Alpine-Pyrenean Orogen reliefs. Main tectonic transport has been drawn and relative age uplift.

Fig. 10.- Mapa tectónico esquemático y corte mostrando el modelo tectónico propuesto para la terminación occidental de los relieves del Orogeno Alpino-Pirenaico. Las flechas indican la dirección de transporte tectónico y las edades del levantamiento.

to the west (As Pontes Basin) during Late Oligocene-Early Miocene times. In the southern border of the Cantabrian Mountains, (northern Duero Basin) much of the Tertiary deposits are deformed, except the uppermost formations that onlap, and are syntectonic with the Alpine structures. The age of these syntectonic deposits ranging from Oligocene to early Upper Miocene (Colmenero *et al.*, 1979; Corrochano, 1989; Herrero *et al.*, 2004). However, in the western part, the youngest formation (Medulas Fm) is deformed by the north verging thrusts of the Galaico-Leoneses Mountains. These observations would suggest that tectonic activity in the Cantabrian Mountains had ceased while in the Galaico-Leoneses Mountains north verging-thrust activity continued. This observation is in agreement with the structural mapping where Galaico-Leoneses Mountains structures offset the Cantabrian Mountains structures (Fig. 3). In addition, the NE-SW strike-slip faults that are related with the north vergent thrusts, present a vertical component that have been dated in Portugal as Upper Miocene-Quaternary in age (Cabral, 1989; Carvalho *et al.*, 2006). NE-SW faults are associated with active seismicity (González-Casado and Giner, 2000; Rueda and Mezcua, 2001; López-Fernández *et al.*, 2004; Martínez-Díaz *et al.*, 2006) and this together with the intense drainage reorganisation observed (Martín-González, 2009), would suggest that there was a significant Late Miocene-Quaternary activity along these faults.

It is worth mentioning that on the Iberian Plate, after the Middle Miocene, the maximum horizontal compression changed due to the gradual relocation of the active plate boundary to the south of Iberia (Dewey *et al.*, 1989; Srivastava *et al.*, 1990; Andeweg, 2002). Therefore, a part of the NW Iberian Peninsula tectonic activity was produced by intraplate propagation of the compressive deformation from the Betic Chains (SE Iberian Peninsula).

7. Conclusion

The geology observed along the western termination of the Alpine-Pyrenean Orogen relieves resulted from the superposition of two mountain ranges (Cantabrian Mountains and Galaico-Leoneses Mountains) and a complex tectonic evolution. The Cantabrian Mountains (CM) were emplaced southward along a basal north dipping thrust (CBT). Westward, the CBT emerges as an E-W imbricate thrust system with south vergence. The monoclinal flexure related to the north dipping thrust transforms into a tectonic pop-up. E-W thrusts decrease displacement westward and finally they link up with N-S trending arch structures (Ibias-Ancares and Rúa-Vilalba structures) explaining the termination of the E-W-trending ranges of the Cantabrian Mountains and the N-S distribution of Vilalba, Monforte de Lemos and Sarria depression. These two structures partially accommodate the CBT shortening to the north.

The Galaico-Leoneses Mountains (GLM) were emplaced northward by north-verging thrusts. The shortening along these thrusts was compensated by NE-SW left-lateral strike-slip faults in the west. These faults link with the NE-SW corridors of the Iberian Massif (Braganza-Vilariça and Vila Real-Verín). The GLM structures offset the CM structures.

Based on the observed structures, four main Alpine regions have been established in the NW Iberian Peninsula: (1) the Astur-Galaica region (AGR) in the western part of the Cantabrian Mountains, characterized by thrusts with south vergence, that represent the continuation of the South Pyrenean Zone structures, (2) The Galaico-Leoneses Mountains (GLM), characterized by thrusts with north vergence, (3) The Rías Baixas-Terra Chá region (RBT) characterized by strike-slip faults with no relevant associated relief but with seismicity, which represents the less-deformed foreland.

The Tertiary sediments of the El Bierzo depression, which today are preserved in small and isolated depressions, were formerly part of a widespread foreland basin located around the Cantabrian Mountains, that was dissected and eroded by the uplifting of the GLM. Thus, the Tertiary-age depressions of El Bierzo and O Barco are located in an E-W tectonic pop-down bounded by the CM and GLM thrusts. The Tertiary-age Monforte, Sarria and Vilalba depressions are limited to the east by the N-S structure of Rúa-Vilalba. Subsequently, NE-SW strike-slip faults offset the Rúa-Vilalba structure and dissected the Tertiary sediments.

The geological data presented in this work suggest that Alpine deformation in the NW Iberian Peninsula began in the northeast (Oviedo Basin) during the Eocene. In the western and southern areas, tectonic activity commenced during the Oligocene-Early Miocene (El Bierzo and As Pontes Basin). The Cantabrian Mountains tectonic activity ended at the beginning of the Late Miocene. However, deformation continued in the GLM through the Late Miocene and Quaternary. Thus, the tectonic activity in the GLM was longer lasting than in the CM, and is also supported by apatite fission tracks studies (Martín-González *et al.*, 2008). In that study it was also observed that uplift of the CM began in Oligocene times, while the GLM uplift commenced during the Middle and Late Miocene.

Acknowledgments

The authors wish to thank C. Connors for critically reading the manuscript and C. Curran for making useful linguistic assistance. We also thank J. Álvarez Pulgar and T. McCann for the suggestions and comments made in the review of this article that have contributed to the improvement of the final version of the manuscript.

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