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The boundary between the eastern and western domains of the Pyrenean Orogen: a Cenozoic triple junction zone in Iberia?

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Abstract

The Cantabrian Transitional Area (CTA) is located in the eastern portion of the Cantabrian Mountain Range of the northern Spain. It represents the most important internal boundary within the Upper Cretaceous to Cenozoic E–W elongated Pyrenean Orogen. In the south-verging portion of this orogen, the CTA divides the western thick-skinned Cantabrian Domain, which accommodated for a limited portion of the total N–S oriented orogenic shortening, from the Pyrenean realm to the east, where the south-verging frontal structures are characterised by a marked thiN–Skin style of deformation, and significantly contributed to accommodate the total shortening. In the Cantabrian Transitional Area, Cenozoic syn-orogenic left-lateral, right-lateral and reverse dip-slip movements have occurred along different directions, postdating early-orogenic extensional structures. The latter indicate that the southern portion of the study area formed the eastern termination of the northward concave roughly E–W oriented proto Duero Foreland Basin. This basin was flanked to the north by the thick-skinned proto Cantabrian Belt, which included in its easternmost part the northern portion of the Cantabrian Transitional Area. Onset of right-lateral strike-slip tectonics along the WNW-ESE striking Ubiernal-Venatniella Fault System, which locates to the SW of the CTA and crosses the entire Cantabrian Belt and its formerly southern foreland basin, caused the dislocation of the belt-foredeep system. Contextually, thiN–Skinned structures belonging to the eastern domain of the Pyrenean Orogen laterally propagated and incorporated the eastern part of the proto Duero Foreland Basin. Coexistence of right-lateral and reverse movements to the west and to the east, respectively, determined the onset of an intrabelt compression at the boundary between the Cantabrian and Pyrenean domains, which was the ultimate act of the fusion of the two domains into a single orogen.

Paradoxically, this fusion has basically occurred due to the penetration of the NW-SE-striking intraplate right-lateral transpressive system of the Iberian Chain into the Cantabrian Domain of the Pyrenean Orogen. Cenozoic right-lateral reactivation of the

Ubierna Fault System, in fact, is part of a NW-SE striking intraplate strike-slip transpressive system, which to the south-east includes the Iberian Chain until the Mediterranean Sea and that, in the western termination of the Ubierna Fault System, branches off into three main splay faults, which are the Ventaniella and Leon faults, and the Duero frontal thrust. Taking into account the role of this Cenozoic transpressive system allows to drastically reduce the gap between plate kinematic reconstructions and geological evidences. This implies that, despite the limited amount of displacement, the Iberian Chain and the Ubierna-Ventaniella systems must be elevated to the rank of microplate boundary, which divided two sectors of the Iberian Plate. Accordingly, the intersection between this system and the Pyrenean Orogen, which occurs in the CTA, must be regarded as a triple junction zone.

1 Introduction

The eastern portion of the Cantabrian Mountains (northern Spain) represents the transitional area, hereafter named Cantabrian Transitional Area, between two distinct domains of the Pyrenean doubly-vergent orogen (Fig. 1), which developed in late Cretaceous to Cenozoic age due to the subduction of the Iberian Plate underneath the Eurasian one (Choukroune et al., 1989; Roure et al., 1989; Muñoz, 1992; Verges et al., 1995; Pulgar et al., 1996; Teixell, 1998; Gallastegui, 2000; Vergés et al., 2002; Pedreira et al., 2007). To the east, in the Pyrenean Domain, the far-travelled frontal structures of the south-verging portion of the orogen are characterised by a thiN–Skin style of deformation (e.g. Choukroune et al., 1989; Muñoz, 1992; Teixell, 1998; Pedreira et al., 2007) (Fig. 1b). Conversely, the western portion of the Pyrenean Orogen, namely the Cantabrian Domain, is characterised by a thick-skin style of deformation also in its southernmost frontal portion (Alonso et al., 1996; Pulgar et al., 1996; Gallastegui, 2000), which accommodated only for few kilometres of south-directed movements (Tavani et al., 2011a). In this western domain most of the convergence was accommodated in the north-verging portion of the orogen (Gallastegui, 2000; Pedreira

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et al., 2007) (Fig. 1b), where the amount of Cenozoic shortening was about 90 Km (Gallastegui et al., 2002). Such a behaviour of the Cantabrian Domain is particularly evident in its western termination, toward which the southern foreland basin (i.e. the Duero Basin) progressively disappears and contractional structures mostly include strike-slip faults oriented consistently with a roughly N–S to NNW-SSE oriented shortening direction (De Vicente et al., 2011; Martin-Gonzalez and Heredia, 2011). The Cenozoic uplift of the western sector of the Pyrenean Orogen mostly related with indentation tectonics (Fig. 1b) (e.g. Gallastegui, 2000; Pedreira et al., 2007), which caused coeval north-directed subduction of Iberain lithosphere (up to the lower crust) and scraping off of the upper Iberian crust above a north verging sole-thrust. Thickening of the lower crust was the main responsible for the uplift of the Cantabrian Mountains, as witnessed by the correspondence, along the strike of the belt, between the thickness of the indenting lower crustal body (corresponding to the high Vp velocity body in P4) and the topographic elevation.

Early studies in the Cantabrian Transitional Area pointed out the existence of a complex pattern of Cenozoic dip-slip and strike-slip movements (e.g. Hernaiz, 1994; Serrano et al., 1994; Espina et al., 1996a). However, until recent years these have been mostly considered as local complications, and the orogenic architecture of the southern Pyrenees has been proposed also in the Cantabrian Domain and in the Cantabrian Transitional Area. In particular, a north-dipping low-angle thrust accommodating for about 20 km of south-directed shortening has been inferred to be present below the Cantabrian Mountains (Alonso et al., 1996). Such an interpretation, however, has been recently confuted by Tavani et al. (2011a), who pointed out that microseismicity of the Ventaniella Fault (López-Fernández et al., 2004), which should be displaced at least of 5 km by this supposed thrust, provides the image of a roughly integer fault zone, down to at least 16 km of depth. This being incompatible with the existence of an important north-dipping low-angle thrust below the Cantabrian Mountains.

In recent years there has been a renewed interest in studying the structural evolution of the area. This mainly, but not only, because in its southern portion will locate an

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experimental site for CO_2 storage. Fracture data collected in the framework of CO_2 reservoir characterisation (Tavani et al., 2011a; Tavani and Muñoz, 2012; Quintà et al., 2012; Quinta and Tavani, 2012), together with other structural studies (e.g. Pedreira et al., 2007; Soto et al., 2008; De Vicente et al., 2011; Carola et al., Accepted), shed new lights on the Mesozoic and Cenozoic evolution of major features of the Cantabrian Transitional Area. In particular, both De Vicente et al. (2011) and Tavani et al. (2011a) recognised the importance of syn orogenic strike-slip tectonics, and the marked change in deformation style across the Cantabrian Transitional Area has been pointed out by Tavani et al. (2011a) and Carola et al. (2012). The structural complexity of this portion of the Pyrenean Orogen is further confirmed by early-orogenic mesostructures (Quinta and Tavani, 2012), which support an early Cantabrian affinity of the westernmost sector of the Pyrenean Domain.

This work aims at presenting a comprehensive and kinematically validated tectonic reconstruction of the area. The proposed tectonic framework is based on both newly presented and previously published structural data, which allow for the consistent interpretation of the complex macrostructural pattern of this transitional zone. At the end of the work, geological implications of this reconstruction are discussed at the plate tectonic scale.

2 Geological outline

The Cantabrian Transitional Area (Fig. 2a, b) represents an outstanding example of inversion tectonics, with all the major fault systems have a pre-orogenic origin (Fig. 2c, d) (García-Mondéjar et al., 1986; Lepvrier and Martinez-Garcia, 1990; Malagon et al., 1994; Pulgar et al., 1999; Cámara, 1997; Espina et al., 2004; Alonso et al., 2009; Tavani and Muñoz, 2012). To the south, the Ubierna-Ventaniella Fault System and the western portion of the Sierra de Cantabria Fault are at least Triassic in age (e.g. Tavani and Muñoz, 2012). These were reactivated during the late Jurassic to early Cretaceous rifting associated with the opening of the Bay of Biscay and, together with a system of newly formed NE-SW striking and NW-dipping transversal faults (Tavani and Muñoz, 2012), they formed the southern boundary system of the Mesozoic Basque-Cantabrian Basin (Rat, 1988; Malagon et al., 1994; García-Mondéjar et al., 1996) (Fig. 2c). During Cenozoic convergence, the Ubierna-Ventaniella Fault System was reactivated as a right-lateral element (Hernaiz, 1994; De Vicente et al., 2011; Tavani et al., 2011a) while, in the study area, the Sierra de Cantabria Fault System (which in its westernmost portion is also named Zamanzas Fault Zone) acted as a reverse to left-lateral transpressive element (Serrano et al., 1994; Tavani et al., 2011a; Beroiz and Permanyer, 2011; Quintà and Tavani, 2012). To the north of the Ubierna Fault, the Golobar and Rumaceo fault systems are at least Triassic in age too (Espina et al., 2004; Tavani and Muñoz, 2012). They strike parallel to the Ubierna Fault and have been reactivated as extensional elements during the late Jurassic to early Cretaceous rifting. Later, during Pyrenean orogeny, they firstly acted as right-lateral transpressive elements and then as left lateral structures (Tavani et al., 2011a). More to the north, the structural trend changes and the major feature is the E–W striking and south-dipping Cabuerniga Fault, which is at least Triassic in age (e.g. Rat, 1988). In this area roughly N–S striking transversal extensional faults (i.e. Pas and Ramales faults) developed during the late Jurassic to early Cretaceous extensional reactivation of the Cabuerniga Fault (Tavani and Muñoz, 2012). These N–S striking transversal elements were positively inverted during the subsequent contractional stage (Tavani et al., 2011a), due to an E–W oriented late-orogenic compression, being such a stage responsible also for the previously mentioned left-lateral reactivation of the WNW-ESE striking Golobar and Rumaceo faults.

A complex stratigraphic architecture characterises the study area, relating with its complex and polyphasic tectonic history. In a first approximation two stratigraphic domains can been individuated (Fig. 3): (1) The Basque-Cantabrian Basin, which includes thousands of metres of Mesozoic sediments, and (2) the Asturias-Duero-Ebro Domain that, with the exception of the Oviedo Basin, includes only a thin package of Mesozoic sediments (Alonso et al., 1996; Espina et al., 2004). In the Basque-Cantabrian Basin,

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siliciclastic rocks of the Permo-Triassic Buntsandstein facies unconformably overlie the Paleozoic basement, and were deposited during the first, early Triassic, rifting. These rocks are overlain by Triassic dolostones and carbonates of the Muschelkalk facies, and by evaporites and clays of the Keuper facies (Lanaja, 1987; García-Mondéjar et al., 1996; Espina, 1997). Upper Triassic to Middle Jurassic rocks include limestones, dolostones, evaporites and marls (e.g. Quesada et al., 1993). Conglomerates, sandstones and clays were deposited during the main late Jurassic to early Cretaceous rifting (Lanaja, 1987; Pujalte et al., 1996). Upper Cretaceous limestones and marls unconformably overlay Lower Cretaceous rocks. The Cenozoic sediments mostly include Paleocene to Miocene conglomerates and sandstones (Hernaiz Huerta and Solé Pont, 2000). With the exception of the Asturian Basin, the Duero-Ebro-Asturian Domain is characterised by a thinner (even absent) Mesozoic package (Lanaja, 1987; Floquet, 2004), and Cenozoic sediments of this domain frequently directly overly the Paleozoic basement (Lanaja, 1987).

From a structural point of view, six orogenic sub-domains can be individuated in the area (Fig. 4), whose macro and mesostructural features are described in the following sections.

3 Orogenic sub-domains

3.1 The foreland basins

In the study area, the Duero and Ebro foreland basins flank to the south the Pyrenean Orogen. Cenozoic syn-orogenic sediments fill both basins (e.g. Alonso et al., 1996; Santisteban et al., 1996; Muñoz-Jimenez and Casas-Sainz, 1997) and overlay the pre-orogenic substratum, which includes a variable thickness of Triassic to Paleocene sediments (frequently less than few hundreds of metres), and the underlying Paleozoic basement (Lanaja, 1987). Despite of their similar stratigraphic architecture, the two basins display important structural differences (Fig. 5).

The Sierra de Cantabria Thrust Sheet delimits to the north the Ebro Foreland Basin (Sect. 1 to 3 of Fig. 5). The detachment level of this thiN–Skinned element is provided by Triassic evaporites of the Keuper facies. Along this weak level the thrust sheet overrode the slightly north-dipping layers of the foreland basin, being the amount of displacement in the central portion of this arched structures at least 20 km (Riba and Juardo, 1992; Martínez-Torres, 1993; Muñoz-Jimenez and Casas-Sainz, 1997). In this area the Ebro Basin displays the typical geometry of a foreland basin, with pre-orogenic layers shallowly dipping toward the north (i.e. toward the belt), and syn-orogenic sediments thickening toward the same direction (their thickness exceeds 5 km near the Sierra de Cantabria Thrust Sheet). The thickness of Mesozoic sediments abruptly increases across the Sierra de Cantabria Thrust, indicating that this fault largely reworked the southern margin of the Mesozoic Basque Cantabrian Basin.

The Duero Foreland Basin displays a very different geometry (Sects. 4 to 8 of Fig. 5). It consists of an E–W trending regional synclinorium extending for about 100 km from the Ubierna Fault System to the east, to the Galician area to the west. In the northern limb layers are gently south-dipping at both tips, while become near vertical to overturned in the central portion. Roughly E–W striking thrusts and back-thrusts affect this limb (e.g. Gallastegui, 2000), the north-dipping Duero Frontal Thrust being the most important structure belonging to this reverse fault systems. Paleozoic to Upper Cretaceous rocks in the hangingwall of this thrust overrode the Cenozoic materials of the Duero Basin. Cutoff lines of the Duero Front Thrust (Gallastegui, 2000) indicate a very limited displacement (in comparison with the Sierra de Cantabria Thrust), whose average value is less than 4 km (it locally reaches about 8 km). The depocentre of the basin is located to the south of the Duero Frontal Thrust, where the thickness of syn-orogenic materials is less than 3 Km. Toward the west the substratum of the foredeep rises up and, in the Galician Area, Paleozoic (even Pre-Cambrian) rocks are widespread. However, few exposures of Cenozoic sediments are present there, representing the rest of the Duero Foreland, which from late Eocene to Miocene age was including also this area (Martin-Gonzalez and Heredia, 2011).

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3.2 The Plataforma Burgalesa Domain

The Plataforma Burgalesa Domain interrupts the structural continuity between the Ebro and Duero basins. At a regional scale this domain is a SSE-dipping monocline bounded to the south by the right-lateral Ubierna Fault System (Tavani et al., 2011a) and to the north by the western termination of the arc shaped Sierra de Cantabria Thrust (Fig. 6). The Ubierna Fault System includes the Ubierna Fault and the south-eastern termination of the Vantaniella Fault (Fig. 6). As previously mentioned these elements formed the south-western boundary of the E–W elongated upper Jurassic to lower Cretaceous Basque-Cantabrian Basin. Mesozoic extensional architecture is well-imaged in seismic sections striking at an high angle to the Ubierna Fault, where extensional growth geometries are recognisable (Fig. 7). In the hangingwall of the Ubierna Fault the thickness of upper Jurassic to lower Cretaceous syn-rift sediments increases toward NNE, passing from less than 1 s (TWT) close to the fault, to about 2 seconds away from it. In the vicinity of the fault, almost flat-lying reflectors of the syn-rift sequence are characterised by onlap relationships with the underlying upper Triassic to middle Jurassic pre-rift units, which dip toward NNE and attain a sub horizontal attitude only away from the fault. Below these NNE-dipping pre-rift reflectors, the transparent seismic facies belongs to the Triassic evaporites. Further below, sub horizontal reflectors of the Permo-Triassic Buntsandstein facies are imaged. As pointed out by Tavani et al. (2011a), these geometries are diagnostic of an extensional forced fold (e.g. Brown, 1980; Laubscher, 1982), where the Triassic evaporites ensured the decoupling between faulted Paleozoic rocks and folded Mesozoic cover sequence. The thickness of the entire Mesozoic sedimentary package reduces to few hundreds of metres in the area between the Ventaniella and Ubierna faults. Along the central portion of the Ubierna Fault, rocks of similar age are exposed in the hangingwall and in the footwall, as recognisable despite the presence of several second order folds and faults in the southern block of the Ubierna Fault. This, together with the well preserved Mesozoic extensional architecture and with macro- and meso-structural data (Tavani et al., 2011a), highlights an almost exclusive strike-slip behaviour during the Cenozoic inversion stage, with a very subordinated reverse component. Consistently with WNW-ESE directed right-lateral wrench tectonics, evidences of dip-slip inversion are found along the three main transversal elements striking at an high angle to the Ubierna Fault, namely the Ayoluengo, Rojas and Hontomin transversal elements. This is particularly evident across the Hontomin Transversal Fault (Fig. 8), where the thickness of the syn-rift sedimentary package reduces toward SE, allowing to infer the presence of a deeply rooted NW dipping Mesozoic extensional faults. The same fault has been positively inverted during Cenozoic, as witnessed by the uplift of its hangingwall and by the presence of Cenozoic contractive growth strata. Similarly, the Rojas System, being the contractional horsetail termination of the Ubierna Fault System (Fig. 6), can be interpreted as related with an inverted extensional transversal fault. In fact, well data indicate the presence of many hundreds of syn-rift sediments immediately to the west of this element, while to the east Cenozoic sediments in many cases directly overlie the Paleozoic basement (Lanaja, 1987). The inversion of the three above mentioned NW-dipping extensional transversal elements is responsible for the staircase geometry of the Plataforma Burgalesa Domain, which along a WNW-ESE direction is divided by these elements in three sectors, where exposed rocks are (from the east to the west): Cenozoic, Upper Cretaceous, and Jurassic to Cretaceous in age (Fig. 6b).

The thickness of Mesozoic sediments, which strongly reduces to the SW of the Ubierna Fault, further reduces to the south of the Ventaniella Fault. Seismic sections located to the SW of the western termination of the Ubierna Fault, show that the south-dipping northern limb of the Duero Basin continues in this area. It is in fact well recognisable, despite the slight deformation produced by the Ventaniella Fault (Fig. 9), which in this area has a negligible, and frequently opposite, apparent vertical displacement. Toward SE, the reverse component of the Ventaniella Fault slightly increases being this fault, however, characterised by a flipping hangingwall transport direction (Fig. 9).

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3.3 The SW Basque Pyrenees

The southern leading structure of the Basque Pyrenees is the Sierra de Cantabria Thrust Sheet (Fig. 10). Anticlines and synclines in the hangingvall of the Sierra de Cantabria Thrust have wavelengths ranging from 1 to 20 km, and the Triassic evaporites provide the deeper decollement level (Martínez-Torres, 1993). Both the depth of detachment and the folds wavelength increase to the north, in correspondence of the WNW-ESE striking Bilbao Anticlinorium (Fig. 2), which forms part of the transitional area between the south- and north-verging Basque Pyrenees (Gómez et al., 2002; Pedreira et al., 2007; Ábalos et al., 2008). The Sierra de Cantabria Thrust Sheet has a northward concave shape, and the frontal anticline and the trailing synclinal system strike about E–W in the central portion of the thrust sheet, while they progressively attain a NW-SE and WSE-ENE orientation to the west and to the east, respectively. In detail, the thrust sheet is divided in two sectors flanking to the north the Ebro Basin and the Plataforma Burgalesa Domain, respectively. All available data, including a deep well (Well Corrès-1 in Fig. 10), have always supported the interpretation of the eastern portion of the Sierra de Cantabra Thrust Sheet as a large-displacement thiN–Skinned ramp-related anticline (Fig. 5, Sects. 1 to 3). Things become more complex to the west of the Pancorbo Transversal System, which is an anticline including a northern NW-SE striking segment and a southern segment striking about N–S. To the west of this transversal structure, the hangingwall of the thrust includes several second order folds paralleling the trend of the thrust sheet (which further to the west attains a NW-SE strike) and also a more external and open anticline, namely the Villalta Anticline of the Plataforma Burgalesa Domain. The wavelength of the main anticline (i.e. the Oña Anticline) increases with respect to the eastern sectors, and available deep wells indicate the absence of Cenozoic materials below both the western portion of Sierra de Cantabria Thrust Sheet (Navajo-1 Well) and the Plataforma Burgalesa Domain (Rojas NE 1 Well) (Lanaja, 1987).

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Rocks exposed along the frontal anticline of the Sierra de Cantabria Thrust mostly span in age from late Cretaceous to Cenozoic. There are few small exceptions, which are mostly located in the western sector of the thrust sheet. The Oña Anticline, where Triassic and Jurassic rocks are exposed, being the most important one. Another important difference between the western and eastern sectors of the Sierra de Cantabria Thrust Sheet concerns the amount of "admissible" displacements along the frontal thrust. As previously mentioned, to the east of the Pancorbo System the south-directed displacement exceeds 20 km (Riba and Juardo, 1992; Martínez-Torres, 1993; Muñoz-Jimenez and Casas-Sainz, 1997). Conversely, to the north of the Plataforma Burgalesa Domain, the displacement associated with the Sierra de Cantabria Thrust is reduced, probably to less than few km. This is testified by the following evidences: (1) the thrust fault progressively disappears westward of the Oña Anticline; (2) the Navajo −1 well did not encountered any important repetition of the multilayer, and found Paleozoic rocks below a thick package of Triassic evaporites (Lanaja, 1987); (3) the trace of the E–W striking Huidobro Anticline, which locates immediately to the south-west of the Sierra de Cantabria Thrust, is recognisable in the western termination of the Oña Anticline (see Fig. 3 in Quintà and Tavani, 2012), geometrically imposing a limited amount of displacement (i.e. about a couple of km). This sets problems for the interpretation of the Sierra de Cantabria Thrust as resulting from the inversion of a single extensional fault, as it arise a drastic and sharp lateral decreasing in the amount of shortening. A consistent interpretation, reconciling all the illustrated features, is that the Sierra de Cantabria Thrust Sheet actually resulted from the joining of two inversion-related anticlinal systems, developed due to the positive inversion of distinct and formerly distant WNW-ESE striking Mesozoic extensional fault systems. These extensional faults controlled the distribution of the ductile triassic evaporitic level that, in turn, controlled the style of deformation during the inversion stage. In the proposed interpretation, the eastern portion of the thrust sheet resulted from ramp-related folding (Suppe, 1983; Suppe and Medwedeff, 1990; Tavani and Storti, 2006), as immediately to the south of the inverted fault the triassic evaporites were not present. Conversely, to the east, the limit

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of Keuper evaporites was located in a southernmost position (i.e. the Ubierna Fault area). Shortening in this western area was mostly accommodated by decollement folding (e.g. Chamberlin, 1910; Buxtorf, 1916; Jamison, 1987), which allowed for the development of an higher number of anticlines, distributed along a wider cross-sectional zone, which is a typical behaviour in presence of a ductile decollement level (e.g. Lujan et al., 2003). The Pancorbo Transversal System is here interpreted as an accommodation structure resulting from the reactivation of an inherited transversal extensional element, which laterally delimited the keuper facies distribution during Mesozoic. The proposed interpretation implies a smoothed westward decreasing of the cumulative displacement, which to the west was accommodated by multiple structures. Coherently with this, it must be assumed that the Sierra de Cantabria Thrust is a late-stage fault, resulting from the late-thrusting linkage of formerly distant fault systems, which will be detailed in the discussion.

The development of roughly E–W striking anticlines and synclines is, however, one of the later stages of the Cenozoic deformational sequence recorded in the area. Comparison between mesostructures hosted in upper Cretaceous rocks of the Plataforma Burgalesa Domain and of the southern limb of the Villarcayo Syncline (Quinta and Tavani, 2012), has revealed a common complex history that is summarised in (Fig. 11). In both areas the oldest deformational pattern, which affect all the upper Cretaceous sequence, is represented by Cenozoic extensional structures developed during thermal subsidence of the basin (Fig. 11a). This event was postdated by two early-orogenic extensional stages, associated with outer-arc extension in the peripheral bulge and along-foredeep stretching, respectively (Fig. 11b). In both areas, and for both events, mesostructural data indicate a WSE-ENE elongated foredeep, thus forming an angle of about 20° with the present day trend of both Duero and Ebro foredeeps. These stages were in turn followed by a NNW-SSE oriented layer-parallel shortening event (Fig. 11c), which caused the right-lateral reactivation of inherited WNW-ESE striking structures, and the development of WSW-ESE striking folds, being the Huidobro Anticline of the Plataforma Burgalesa Domain the major one. Reverse reactivation of

WNW-ESE striking faults, and thus development of anticlines having this trend (like the Villalta and Oña anticlines) has occurred during a later stage. The two domains to the north and to the south of the Sierra de Cantabria Fault differentiated in a later deformation stage. To the north of the Sierra de Cantabria Thrust, an E–W to WSW-ENE oriented compression has occurred during this final deformation stage (Fig. 11d), causing left-lateral reactivation of WNW-ESE striking elements, including the western termination of the Sierra de Cantabria Fault, and development of N–S striking compressive structures.

3.4 The Eastern Cantabrian Belt

The transition between the Basque Pyrenees and the Eastern Cantabrian Belt occurs across the Cenozoic Valmaseda Monocline, which is a 60 km-long WSW-ENE striking and SSE-dipping monocline (Figs. 2 and 10). To the NW of this element, in the Eastern Cantabrian Belt, rocks mostly range in age from Triassic to early Cretaceous. The macro and mesostructural Mesozoic extensional architecture is outstandingly preserved in the northern portion of the area, while Cenozoic deformation appears to be less developed.

In the northern part of this sub-domain, the major feature is the E–W striking and south-dipping Cabuerniga Fault (Figs. 2 and 12a). This is probably a Paleozoic fault, reactivated as an extensional element during both Triassic and upper Jurassic to lower Cretaceous rifting events (Garcia-Mondejar et al., 1986), and later inverted during Pyrenean orogeny. The Pas and Ramales anticlines strike about N–S, and represent inherited upper Jurassic to lower Cretaceous transversal elements (Tavani and Muñoz, 2012), which have been positively inverted during the Cenozoic. As reported in Tavani and Muñoz (2012), mesostructures hosted in upper Triassic to lower Cretaceous sediments exposed along the Cabuerniga Fault System are mostly arranged in a rather simple extensional pattern. This includes joints and extensional faults striking about N10° and N100° and a subordered NNW-SSE-striking extensional fault set (Fig. 12b). To the east, this extensional assemblage is postdated by NW-SE-striking veins, frequently describing an echelon pattern consistent with an E–W oriented right-lateral movement (Fig. 12c). Surprisingly, with the exception of this vein set, the Cenozoic activity of the Cabuerniga Fault System is poorly evident. Similarly, in the central and western portions of the fault, mesostructures have almost entirely developed during the Mesozoic extensional stages. However, few right-lateral transpressive mesostructures have been found along the central and western segments of the fault, which could be interpreted as Cenozoic in age. In its central portion, the Cabuerniga Fault has Devonian rocks and Jurassic marls in the northern and southern block, respectively. Locally, the contact is provided by a steeply north-dipping plane (Fig. 12d), with associated right-lateral transpressive to purely strike-slip slickenlines (Fig. 12e). Consistently with this, the damage zone of the northern block (i.e. the Devonian block) hosts abundant right-lateral mesofaults, which include both synthetic elements striking WNW-ESE and E–W striking faults paralleling the master fault (Fig. 12f). Further to the west, south-dipping upper Triassic to lower Jurassic limestones in the southern block of the Cabuerniga Fault host tilted reverse (Fig. 13a) and right-lateral (Fig. 13b) assemblages, the latter clearly postdating an early extensional assemblage including two perpendicular joint sets oriented at high angle to bedding and striking, after unfolding, NNE-SSW and WNW-ESE, respectively (Fig. 13b). E–W to WNW-ESE striking right-lateral faults, together with NNW-SSE oriented movements observed along tilted reverse faults, witness for a right-lateral transpressive kinematics of the E–W striking Cabuerniga Fault System, which overprinted Mesozoic extensional elements, and thus it can be very reasonably interpreted as Cenozoic in age. Although the above described elements allow for the definition of the Cenozoic history of the Cabuerniga Fault, it must be remarked once again that the mesostructural pattern observed in the rocks surrounding this element mostly developed during the Mesozoic extensional stages.

Immediately to the south of the eastern termination of Cabuerniga Fault, the WSW-ENE striking Selaya Fault System well fits in the late Jurassic to early Cretaceous extensional tectonics (Fig. 14a). Mesostructural data collected in Jurassic and lower Cretaceous pre- to syn-rift sediments exposed along the north-eastern termination of the Selaya Fault System include only joints and extensional faults. The formers strike NE-SW, NW-SE and NNE-SSW (Fig. 14b). The first two sets are mutually orthogonal, and frequently occur together (Fig. 14c), describer either ladder (with the NE-SW set being the systematic joint set) and grid patterns (e.g. Gross, 1993; Rives et al., 1994). Faults are characterised by the same directions as joints. Few slickenlines have been observed witnessing for an important left-lateral transtensive component along NE-SW striking faults, which provides a stretching direction oriented perpendicular to the NNE-SSW striking joints and faults. Overprinting relationships indicate that NE-SW striking faults developed within an extensional framework and were later reactivated with a left-lateral transtensional kinematics (Fig. 14d) during a WNW-ESE oriented stretching. It is worth remarking that this second stretching direction is oriented about perpendicular to the regional stretching direction associated with the late Jurassic to early Cretaceous rifting (Tavani and Muñoz, 2012). Accordingly, a consistent interpretation is that NE-SW and NW-SE extensional structures in this area, as well as the Selaya Fault System itself, originally developed as either synthetic relay ramp or antithetic extensional interference zones (Gawthorpe and Hurst, 1993), linking the western termination of the Cabuerniga Fault and another extensional fault located more to the south (and today buried below upper Cretaceous limestones) (Fig. 15a). This transfer zone would have been later incorporated into the hangingwall of the Cabuerniga Fault, and thus underwent a WNW-ESE oriented along-strike stretching (e.g. Destro, 1995), which caused the left-lateral transtensive reactivation of the inherited NE-SW striking faults (Fig. 15b).

To the SW, the Rumaceo and Golobar faults affect Paleozoic and Mesozoic rocks. This area represents the transition between the Plataforma Burgalesa Domain and the Cantabrian Belt. Progressively older rocks are exposed to the west (Fig. 16), which allows for the map view of cross-sectional geometries representing the deeper portion of the Plataforma Burgalesa Domain. As previously mentioned, the WNW-ESE striking Rumaceo and Golobar faults are Triassic in age (even older), they have been reactivated during the late Jurassic to early Cretaceous rifting (Espina et al., 2004; Tavani and Muñoz, 2012) and, later, during the Cenozoic inversion stage (Espina et al.,

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2004; Tavani et al., 2011a). Mesozoic rocks are exposed to the east, overlying Triassic evaporites of the Keuper facies. Below these, the Muschelkalk and the Buntsandstein facies are on top of Paleozoic rocks, which are exposed to the west. A strong decoupling exists between Paleozoic rocks and the post-evaporite portion of the multilayer, with evaporites migration testified by salt weld and salt accumulation in synclinal areas. Faults mostly affect the basement, while the upper Triassic to middle Jurassic sequence is only poorly faulted, and drapes the evaporite layer. Cenozoic inversion of the major basement faults has occurred within a right-lateral transpressive framework (Tavani et al., 2011a), and led to the development of anticlines and synclines formed due to the buttressing effect of the extensional faults coring these anticlines. Many faults penetrate into the Mesozoic cover sequence, but with relatively limited displacements (i.e. less than few hundreds of metres). The fact that faults preserve their integrity across the evaporites indicates that, in this area, these did not acted as a regionally important décollement level. In this area the upper Jurassic to lower Cretaceous extensional stage was characterised by the same stretching direction as found in the Cabuerniga Fault area, i.e. about N15/20° (Tavani and Muñoz, 2012), which led to the slightly oblique reactivation of both Rumaceo and Golobar faults. Extensional mesostructures developed during this stage include joints and extensional faults, which are clustered in several sets, the three most important being oriented parallel and perpendicular to the stretching direction, and about NE-SW (Tavani and Muñoz, 2012). WSW-ENE striking pressure solution cleavages and NNE-SSW striking joints and veins pervasively affect Jurassic limestones in the northern block of the Rumaceo Fault, and have been related with the right lateral reactivation of this fault (Tavani et al., 2011a).

In the eastern Cantabrian Belt, the last set of mesostructural data has been collected in the Buntsandstein facies exposed in the Rumaceo, Pas and Cabuerniga areas (opaque area in the map of Fig. 17). These data are reported for the completeness of the work, although they will not be discussed in detail for the reasons illustrated at the end of this section. Mesostructures mostly include joints near perpendicular to bedding, with few rare veins. The dominant joint set strikes NE-SW (Fig. 17), other subordinated sets include elements striking NW-SE, N–S and E–W. These four sets have been found along both the E–W striking Cabuerniga Fault and the WNW-ESE striking Golobar and Rumaceo faults. Clear abutting relationships have not been found, as different joint sets mutually intersect. Mesofaults are characterised by the same trends as joints (Fig. 17). Extensional faults striking about E–W frequently display oblique slickenlines. The few reverse faults are at low angle to bedding and provide a NW-SE oriented shortening direction. Left-lateral faults are clustered along a NNE-SSW striking direction, while right-lateral faults, which are more abundant, strike from about E–W to WNW-ESE and from N–S to NNW-SSE. It is frequently observed that both left-lateral and right-lateral faults reactivate previously developed joint sets and that extensional faults have been later reactivated as strike-slip faults. E–W to WNW-ESE striking right-lateral faults and SW-NE striking reverse faults are here interpreted as Cenozoic in age, consistently with the other data presented in this work. Much more problematic is the definition of the Mesozoic history recorded by these rocks. The presence of multiple post-Triassic deformation stages, in fact, implies difficulties in understanding the development/reactivation history of each joint/fault set and, due to this, defining a reliable main stretching direction for the Triassic extensional stage appears to be difficult.

3.5 The Central Cantabrian Belt

In the central portion of the Cantabrian Mountain Range, Paleozoic rocks deformed during the Hercynian orogeny are widespread. These are represented by middle to late Carboniferous syn to post-orogenic deposits, unconformably overlying pre-Cambrian to Lower Carboniferous rocks (Julivert, 1971; Pérez-Estaún et al., 1991; Dallmeyer et al., 1997). Hercynian and late-Hercynian structures are well preserved, and were reactivated during both Mesozoic rifting and Cenozoic convergence stages (e.g. Pérez-Estaún et al., 1988; Lepvrier and Martinez-Garcia, 1990; Pulgar et al., 1999; Alonso et al., 1996; Gutiérrez-Alonso et al., 2008). The only clear stratigraphic record of the Mesozoic deformational stages of the area is provided by the Asturian Basin (e.g. Lepvrier and Martínez-García, 1990), which is filled with a Mesozoic sequence thinner than

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the equivalent one in the Basque Cantabrian Basin. With the exception of the previously described Duero Frontal Thrust, the major Cenozoic structures of the area, including the Ventaniella and Leon faults, have a Paleozoic origin (Lepvrier and Martinez-Garcia, 1990; Alonso et al., 2009). The NW-SE striking Ventaniella Fault crosses the entire Cantabrian Mountain Range, and its trace is exposed for more that 150 km. It continues to the NW, in the Bay of Biscay, and to the SE, in the Duero Foreland Basin (as seen in seismic lines of Fig. 9), reaching a length of at least 250 km. Hercynian markers in the central portion of the fault are displaced of about 4 km in a right-lateral sense (García-Ramos et al., 1982; Heredia et al., 1990; Alvarez-Marrón, 1995). The Cenozoic age of right-lateral movements along this fault is well-constrained, and it indicated by displaced Cenozoic sediments of the Asturian Basin. The Cenozoic activity of the Leon Fault is, on the contrary, less constrained. In this sense, however, meso (Fig. 18) and macrostructures (Fig. 19a) in the area between the Duero Frontal Thrust and the Leon Fault indicate the existence of an important right-lateral pattern, of which the Leon Fault forms part (Fig. 19a, c). This is well-evident when analysing data collected in both the middle to late Carboniferous syn to post-orogenic deposits and the pre-Hercynian rocks (Fig. 18). Mesostructures in the area, in fact, are characterised by abundant right-lateral elements. Two extensional patterns are also recognisable in syn-to late orogenic sediments, with WNW-ESE and NNW-SSE striking joints and rotaxes (i.e. rotational axis or slip-normal axis) of normal faults testifying for two extensional stages characterised by NNE-SSW and WSW-ENE oriented stretching directions, respectively. It was not possible to determine the relative chronology between these extensional events, whereas abundant right-lateral reactivation of WNW-ESE extensional elements is observed (Carola et al., 2012). As previously pointed out by Heredia (1998), which described a pervasive right-lateral pattern in the area, timing of right-lateral tectonics in the southern portion of the Cantabrian Mountains (i.e. between the Frontal Thrust and the Leon Fault) cannot be fully constrained. However, the paucity of compressional mesostructures, the well-constrained Cenozoic age of right-lateral movements along the Ventaniella Fault to the north and the Ubierna Fault to the

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east, and fracture patterns seen on Cenozoic sediments of the Duero Basin (Fig. 19b), strongly support a Cenozoic age for part of the right-lateral strike-slip assemblages of the area.

4 Discussion

As illustrated in Fig. 1b, indenting of the lower crust is well recognisable beneath the central and eastern Cantabrian Belt (Pedreira et al., 2007) and, in both areas, the thickness of the indenting lower crustal body displays a first order proportionality with the topographic elevation. This forms part of a wider set of evidences supporting the idea that the central and eastern Cantabrian areas formed a single belt (differentiating from the Pyrenean realm located to the east), where Cenozoic mountain building was associated with lower crust indentation. This idea is fully supported by the following additional evidences, pointing out the limited internal deformation of both domains and their similar cross-sectional geometry: (1) in both areas the first-order pre-orogenic architecture is well preserved, both in therm of major structures and of diffuse background fracture patterns. In fact, Cenozoic mesostructures have been found only near major reactivated faults. Moreover, at a bigger scale of observation, the contractional deformation has produced the reactivation of major faults and, as seen in the Rumaceo and Golobar areas, it has produced also folding and/or re-folding of rocks. However, with the exception of the Ubierna, Ventaniella, Leon and Duero Frontal faults, the amount of admissible Cenozoic displacement along inherited faults generally does not exceeds one km. (2) In both areas an uplifted sectors overlying the thickened indenting lower crust exists, which is bounded to the south by an about south-dipping limb. In the Central Cantabrian Belt it is the northern limb of the Duero Basin, which in map view has a slightly northward concave shape and is well-recognisable until it joins the Ubierna Fault (seismic lines d to f in Fig. 9). The Valmaseda Monocline bounding to the south the eastern Cantabrian Belt, represents the natural north-eastern prosecution of the northern limb of the Duero Basin. Between these two sectors of a formerly unique limb, the area between the Ubierna and Rumaceo faults represents a "perturbation zone", whose origin is discussed later. An independent additional datum supporting the existence of an early northward concave proto-Cantabrian belt is provided by mesostructures hosted in upper Cretaceous limestones exposed in the Villarcayo Syncline and in the Plataforma Burgalesa Domain. Mesostructures indicate that these two areas underwent a common early-orogenic deformation (Fig. 11) (Quintà and Tavani, 2012). There, extensional structures developed due to outer-arc extension in the peripheral bulge are overprinted by structures formed due to an along-strike stretching in the foredeep. For both areas, and for both events, mesostructures indicate a forebulge-foredeep system oriented WSW-ENE, i.e. exactly parallel to the strike of the Valmaseda Monocline. Above presented evidences support the existence, before the right-lateral reactivation of the Ubierna-Ventaniella Fault System, of an unique Cantabrian Belt flanking to the north a proto-Duero Foreland Basin, which was including the Plataforma Burgalesa Domain and the Villarcayo Syncline areas (Fig. 20). The presence of the above discussed early-orogenic assemblages several km to the north of the present-day position of the forebulge, indicates that a southward migration of the latter has occurred (Fig. 20). This is consistent with the stratigraphic record of the Duero Basin, which started to act as foredeep at least during middle Eocene (Alonso et al., 1996; Santisteban et al., 1996; Gallastegui, 2000) and where a progressive southward migration of Cenozoic depocentres has been documented (Herrero et al., 2004). These data support the hypothesis of Gallastegui (2000), who indicated that indentation of the lower crust started, during early Eocene, about 100 km to the north of the present day position of the Duero Frontal Thrust. In the light of above presented evidences, the about 100 km of shortening proposed by Gallastegui (2000) and Pedreira et al. (2007) for the entire Cantabrian portion of the orogen, appears to be strongly congruent. Consistently with the foreland-ward migration of both early-orogenic deformation domains and foredeep depocentres, it is found that early-orogenic extensional stages were followed by a NNW-SSE oriented layer parallel shortening event (Quintà and Tavani, 2012), which caused the right-lateral reactivation of inherited WNW-ESE striking faults, including the Ubierna-Ventaniella

Fault System, and the development of WSW-ENE striking compressional structures, including the Huidobro Anticline of the Plataforma Burgalesa Domain. Apatite fission track thermochronology in the western termination of the Cantabrian Mountains mostly provide pre-Cenozoic ages (Grobe et al., 2010), indicating that the Cenozoic uplift was there accompanied by a limited denudation. Conversely, preliminary data from the central portion of the Cantabrian Mountains register the Cenozoic exhumation, which mostly occurred in Oligocene-early Miocene age (Fillon et al., 2011). Growth strata associated with folds in the Ubierna Fault System are Oligocene too (Espina et al., 1996b). This allows to assume that early-orogenic extensional assemblages have developed in early Eocene to early Oligocene age, while layer parallel shortening and right-lateral wrench tectonics, which were suitably coeval with uplift, started not earlier than early Oligocene. A late Oligocene age is indicated for the central portion of the Sierra de Cantabria Thrust (Portero et al., 1979; Muñoz-Jimenez and Casas-Sainz, 1997), while the same thrust is early to middle Miocene in age in its western portion (Olivè Davò et al, 1978), where growth strata associated with the Oña Anticline host tilted conjugate reverse faults indicating a roughly N–S oriented syn-folding compression (Tavani et al., 2011a). Few km to the north of this anticline, Quintà and Tavani (in press) documented the dip-slip reverse reactivation of WNW-ESE striking inherited faults, which previously have been reactivated as right-lateral elements. These informations prove that until middle Miocene the Plataforma Burgalesa Domain and the Villarcayo Syncline formed an unique crustal block, belonging to the foreland basin of the Cantabrian Domain, where right-lateral tectonics occurred along WNW-ESE striking inherited faults (Fig. 20). The breaking of the Cantabrian Belt and of its associated proto-Duero Foreland Basin has occurred during this stage (Fig. 20). ESE-directed movements in the northern block of the Ubierna Fault caused the positive inversion of NW-dipping inherited transversal extensional structures of the Plataforma Burgalesa Domain (namely Ayoluengo, Hontomin and Rojas transversal faults), which resulted in the uplift of this domain. With increasing contraction, the Sierra de Cantabria Thrust Sheet moved southward (considering a fixed foreland) and, contextually, propagated

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westward incorporating the formerly eastern sector of the Proto-Duero Foreland Basin (Fig. 20). To the east of the Pancorbo transversal structure, N–S contraction was mostly accommodated by movements along the Sierra de Cantabria Thrust. To the west of this elements, the presence of Triassic evaporites favoured the development of a cross-sectionally wider fold system, and the cumulative shortening was accommodated by several decollement anticlines, being the Oña Anticline the most important one and the Villella Anticline, in the Plataforma Burgalesa Domain, the more external one. According to this reconstruction, the trace of the Sierra de Cantabria Thrust does not correspond to an unique inverted extensional fault but, instead, it resulted from the late-stage linkage of originally distant structures. It is worth noting that the keuper evaporites are exposed several Km to the north of the Plataforma Burgalesa Domain, nearby the Cabuerniga Fault. The trace of this E–W striking fault is not offset across evaporites, witnessing that, similarly to what observed in the Rumaceo and Golobar area, in this portion of the belt the Triassic evaporites did not acted as an important Cenozoic decollement level. From this it arises that the N–S oriented shortening accommodated by folds of the western portion of the Sierra de Cantabria thrust sheet, must have been transmitted to the north to a deeper decollement level. Consequently, the Valmaseda Monocline is probably affected at depth by few reverse north-dipping faults, similar to those of the northern limb of the Duero Foreland Basin.

The coexistence of right-lateral movements along the WNW-ESE striking Ubierna-Ventaniella Fault System and of reverse south-directed movements along the Sierra de Cantabria Thrust, imposed "space" problems for crustal sectors involved in the orogenic process, causing the onset of an intrabelt E–W oriented compression (Fig. 20) (Tavani et al., 2011a). The question is rather simple and arises from the following geometrical consideration: assuming a fixed foreland, SE- to SSE-directed movements in the crustal block to the north of the Ubierna Fault can be decomposed into south- and east-directed components. The south-directed component can be reasonably assumed to have been partially compensated by the south-directed movements along the western portion of the Sierra de Cantabria Trust Sheet (which explains also the

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reduced amount of shortening in the fold systems of the western potion of the Sierra de Cantabria Thrust Sheet). Conversely, the east-directed component was not compensated, thus imposed an E–W shortening associated with a relative (with respect to the Basque Pyrenees) eastward extrusion of the western portion of the Cantabrian Belt and of the Plataforma Burgalesa Domain. Abundant WNW-ESE striking left-lateral faults affecting upper Cretaceous limestones in the southern limb of the Villarcayo Syncline, and postdating all the other assemblages (Quinta and Tavani, in press), as well as left-lateral reactivation of the WNW-ESE striking Rumaceo and Golobar faults, and the WNW-ESE striking left-lateral transpressive fault zone in the core of the Oña anticline (Tavani et al., 2011a), fully support the existence of this E–W compression, as well as do the N–S striking Pas and Ramales anticlines, which according to Tavani et al. (2011a) formed within the framework of the extrusion tectonics. Reverse mesofaults hosted in the early to middle Miocene growth strata of the Oña Anticline indicate that extrusion tectonics has started not earlier than middle Miocene. Proving the validity of the entire framework requires documenting right-lateral movements along the E–W Cabuerniga Fault, which should have formed the northern portion of the accommodation zone. In this work these evidences have been presented. Summarising, the entire Cantabrian Transitional Area is a complex accommodation zone, across which the south-verging portion of the Pyrenean orogen experienced a strong decreasing of south-directed orogenic shortening. In such a framework, a belt-perpendicular tear fault or tear fault zone is to be expected, which actually is present in the north-verging portion of the orogen (Fig. 1a). Conversely, in the Cantabrain Transitional Area the Cenozoic tectonic framework was moulded by several inherited fault sets, which prevented the development of an unique and simple right-lateral tear system.

At this point it has been demonstrated that the idea of two distinct orogenic domains in the Pyrenean Orogen is consistent with all the available information in their transitional area. This allows magnifying the scale of observation and considering the regional implications of this. Data presented in this work indicate that an important right-lateral wrench tectonics has occurred in the southern portion of the Central Cantabrian

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Belt, along the Ventaniella Fault and in the area between the Leon Fault and Duero Frontal Thrust. This supports the early hypothesis of Tavani et al., (2011a), who suggested that the 15 km of right-lateral displacement computed along the Ubierna Fault, to the west have been transferred to the above cited three major structures. However, while the amount of right-lateral displacement along the central portion of the Ventaniella Fault (i.e. about 4 km, Alvarez-Marrón, 1995) is consistent with this scenario, assuming a cumulative Cenozoic right-lateral displacement of about 10 km for the Leon Fault and the Duero Frontal Thrust is not reasonable. This implies that a westward decreasing of the right-lateral displacement must be assumed. Contextually, in the western termination of the Cantabrian Mountain Range the number of strike-slip structures consistent with an about NNW-SSE oriented shortening increases. NW-SE to WNW-ESE striking right-lateral faults and N–S to NNE-SSW striking left-lateral faults, in fact, are abundant in the western portion of the Iberian Peninsula, which is also characterised by the presence of other intraplate Cenozoic structures (Fig. 1b) (e.g. Cunha and Pereira, 2000; Guimerà et al., 2004; De Vicente et al., 2011; and references therein). Despite the ongoing debate about the detailed evolution of the Cenozoic intraplate stress ?elds of the area (e.g. Liesa and Simón-Gomez, 2007; De Vicente et al., 2009), it is pretty evident that WNW-ESE striking right-lateral faults and N–S to NNE-SSW striking left-lateral faults of the western portion of the Iberian peninsula, together with the WSW-ENE striking Central System, well-fit into an about NNW-SSE oriented compression (Pais, 2012 and references therein), which is the Cenozoic layer parallel shortening direction documented for the Cantabrian Mountains (Quintà and Tavani, 2012). The eastern boundary of these intraplate elements is provided by the Iberian Chain, for which a complex Cenozoic partitioning between strike-slip and reverse movements has been recognised. In particular, De Vicente et al. (2009, 2011) documented a Cenozoic right-lateral strike-slip component along NW-SE oriented elements, which roughly core the chain. Contextually, these authors found a Pyrenean NNE-verging tectonic transport direction in the north-eastern sector of this chain, while reverse faults become west-verging in the western areas. Finally, Cenozoic transport

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direction turns into north-verging in the northern tip of the chain (De Vicente et al., 2009). This northern tip is separated by the exposed south-eastern termination of the Ubierna-Ventaniella Fault System by less than 10 Km. In the area between these elements, several Cenozoic basement structures have been recognised in seiemic sections (Hernaiz Huerta and Solé Pont, 2000), being the San Pedro structural highs the most prominent. These features geometrically and kinematically support the possibility of "forcing" these two hundreds km-long intraplate strike-slip to transpressive structures (i.e. the Ubierna-Venaniella and the Iberian Chain) into a single wide intraplate strike-slip corridor, which would cross the entire Iberian Plate to divide it in two distinct domains (Fig. 21a). From a geological point of view this unification may result questionable, firstly due to the huge length (more than 700 km) compared with the limited right-lateral displacement of this element that, including its several subsidiary structures, probably does not exceed a couple of tens of km, i.e. the value indicated by Tavani et al., (2011a) for the Ubierna Fault. However, this value represents more than 10% of the maximum value of the orogenic shortening in the Pyrenees (Muñoz, 1992), and about 20% of the average orogenic convergence (e.g. Teixell, 1998; Muñoz, 2002; Pedreira et al., 2007). Accordingly, this fault corridor has surely played an important role during the Cenozoic evolution of Iberia, which is particularly evident when the window of observation is enlarged.

Actually, the idea of merging the Iberian Chain and the Ubierna-Ventaiella System may represent a good compromise between the geological reality, i.e. the several intraplate structures described above witness for a non-rigid behaviour of Iberia during Pyrenean orogeny, and the "eulerian" necessity in plate-kinematic reconstructions of modelling the earth's surface as made of narrow deformation zones dividing rigid crustal blocks. In agreement with this, the incorporation of this transpressive element into the Iberian Plate kinematics allows to reproduce a reasonable belt perpendicular syn-orogenic convergence in the eastern Pyrenean realm. This is shown in Fig. 21b, where a tentative reconstruction of the convergence between Iberia and Europe is provided. This solution is able to roughly honours all the available geological information

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at the plate scale, including timing, amount, and direction of convergence (e.g. Muñoz, 2002), but only partially coincides with geometrical constraints provided by identified seafloor spreading anomalies. In particular, this result is obtained under the following assumptions.

1. At the end of Cretaceous Iberia was located less than 50 km to the west of what predicted by magnetic anomaly 34 (e.g. Rosembaum et al., 2002; Vissers and Meijer, 2012).

2. Magnetic anomalies from 33o to 24 (e.g. Roest and Srivastava, 1991; Rosembaum et al., 2002) are ignored, as these impose unreasonable and uncorrectable convergence directions. In particular, as shown in Fig. 2 of Rosenbaum et al. (2002), anomalies from 33o to 30 impose a NE-directed motion of Iberia during late Cretaceous convergence, against a geologically documented NNE-SSW oriented upper Cretaceous shortening direction (Tavani et al., 2011b). Similarly, anomalies 25 and 24 predict a regionally important E–W oriented Cenozoic right-lateral motion in the Pyrenean Mountains, which is simply undocumented.

3. Iberia was divided in two microplates and a relative rotation of 4° has occurred between western and eastern Iberia during Cenozoic.

4. As discussed above, the Iberian Chain and the Ubierna-Ventaniella intraplate systems are elevated to the rank of microplate boundary, which accommodated for about 20 km of right-lateral displacement. This value is sufficient to allow a belt-perpendicular shortening in the Pyrenean realm. In this scenario, and from an eulerian point of view, the intersection between the Pyrenean orogen and the Iberian Chain-Ubierna-Ventaiella system must be considered as a triple junction point (McKenzie and Morgan, 1969).

A final consideration concerns the approach of selectively discarding magnetic anomalies, which one may reject. However, it must considered that the increasing discrepancy

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between plate kinematic studies and geological evidence s at present appears to be irremediable, probably indicating that somewhere an big error has turned into an heavy datum. This is authorising to explore solutions where either part of geological data (e.g. Sibuet et al., 2004) or part of the magnetic anomalies (e.g. Jammes et al. 2009) are essentially ignored.

5 Conclusions

The doubly-vergent Pyrenean Orogen represents the boundary between the Iberian and Eurasian plates, and extends from the Atlantic Ocean to the Mediterranean Sea. It includes two distinct domains developed due to the subduction of the Iberian Plate underneath the Eurasian one. The Pyrenean Domain to the east includes the Pyrenean Mountain Ranges and the Basque area and, in its south-verging portion, it is characterised by far-travelled thiN–Skinned frontal structures. In the Cantabrian Domain to the west, mountain building was associated with indenting and associated thickening of the lower crust, which caused uplift with limited internal deformation of the Cantabrian Mountains. Orogenic shortening in this domain was almost entirely accommodated in the north-verging portion of the orogen. The Cantabrian Transitional Area represents the transition between these two domains. The northern portion of this area formed part of the Cantabrian Domain during the entire orogenic process. The southern area during the early stages of mountain building formed the eastern prosecution of the foreland basin flanking to the south the Cantabrian Domain. In a subsequent stage, the westward propagation of thiN–Skinned structures belonging to the eastern domain of the Pyrenean Orogen caused the incorporation of the south-eastern part of the Cantabrian Transitional Area into the Pyrenean Domain. Contextually, onset of right-lateral strike-slip tectonics along the WNW-ESE striking Ubiernal-Venatniella Fault System, which represents the north-western prosecution of the Iberian Chain, disarticulated the geometry of the Cantabrian Belt and of its associated foredeep. Coexistence of right-lateral and reverse movements to the west and to the east, respectively, determined

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the onset of an intrabelt compression at the boundary between the Cantabrian and Pyrenean domains, which was the ultimate act of the fusion of the two domains into a single orogen.

The Ubierna Fault System, which has been interpreted in the past as the leading edge of thiN–Skinned contractional deformation of the Pyrenean Orogen in the Cantabrian area, has to be regarded as a segment of a thick-skinned intraplate strike-slip belt. This includes the Iberian Chain and the Ubierna Fault System, and the northern splay faults of the latter, which are the Ventaniella, Leon and Duero faults. Consistently, the area between the Ubierna Fault and the Sierra de Cantabria Thrust, i.e. the Plataforma Burgalesa Domain, is an uplifted sector of the Duero Foreland Basin.

The Iberian Chain-Ubierna-Ventaniella system has been successfully introduced in the kinematic framework of Iberia, as a Cenozoic microplate boundary, which allows to drastically reduce the gap between plate-kinematic reconstructions based on magnetic anomalies and geological evidences.

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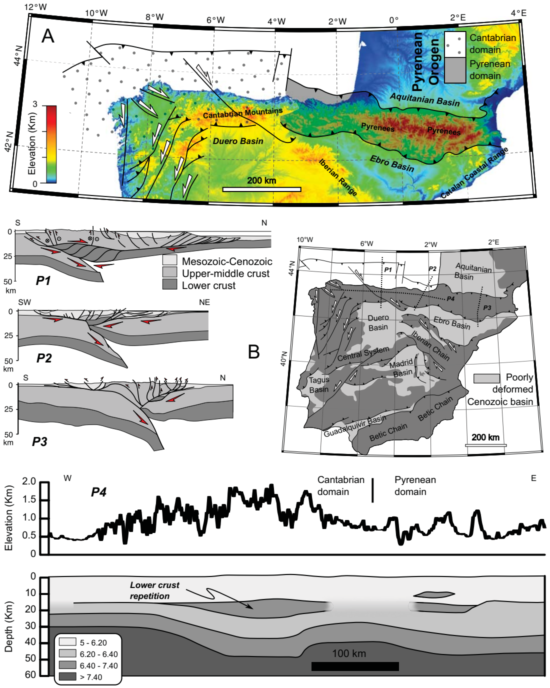

Fig. 1. (A) Elevation map with main faults of the Iberia-Eurasia collisional margin and orogenic domains marked. **(B)** Tectonic sketch map of the Iberian Peninsula (after De Vicente et al., 2009) with crustal scale cross-sections. P1: geological cross section across the Pyrenees (after Muñoz, 1992); P2: geological cross section across the Basque Pyrenees (after Pedreira et al., 2007); P3: geological cross section across the Cantabrian Mountains (modified from Gallastegui, 2000); P4: P wave velocity-depth model along the Cantabrian Mountains and the western portion of the Basque Pyrenees (modified from Pedreira et al., 2007), with corresponding topographic elevation along the same profile.

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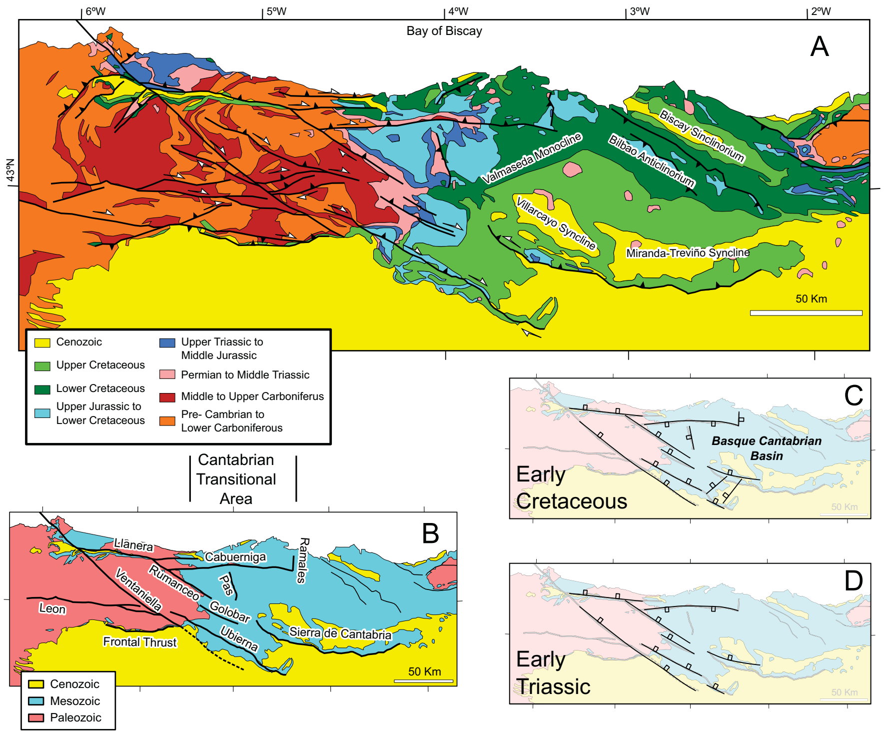

Fig. 2. Geological map of the Cantabrian Transitional Area and surrounding areas (after Tavani et al., 2011a). **(B)** Labelling of major faults. Reconstruction of faults patterns at the end of early Cretaceous **(C)** and Early Triassic **(D)** (modified from Tavani and Muñoz, 2012 and Quintà and Tavani, 2012).

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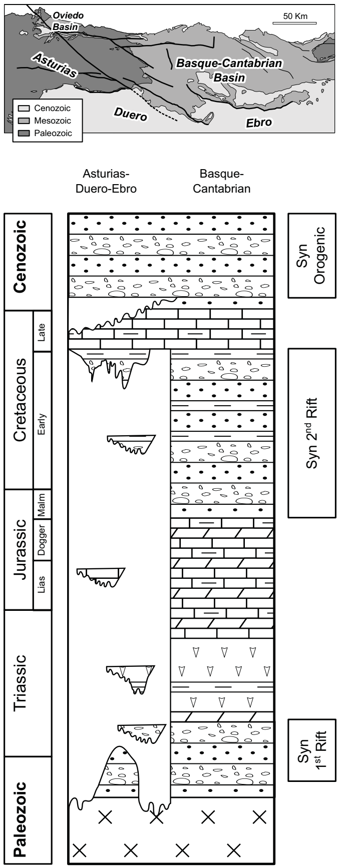

Fig. 3. Synthetic stratigraphy of the area.

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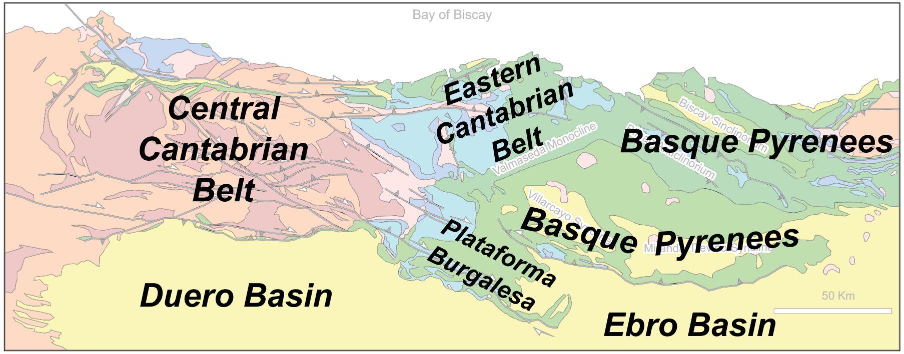

Fig. 4. Cenozoic orogenic sub-domains of the study area.

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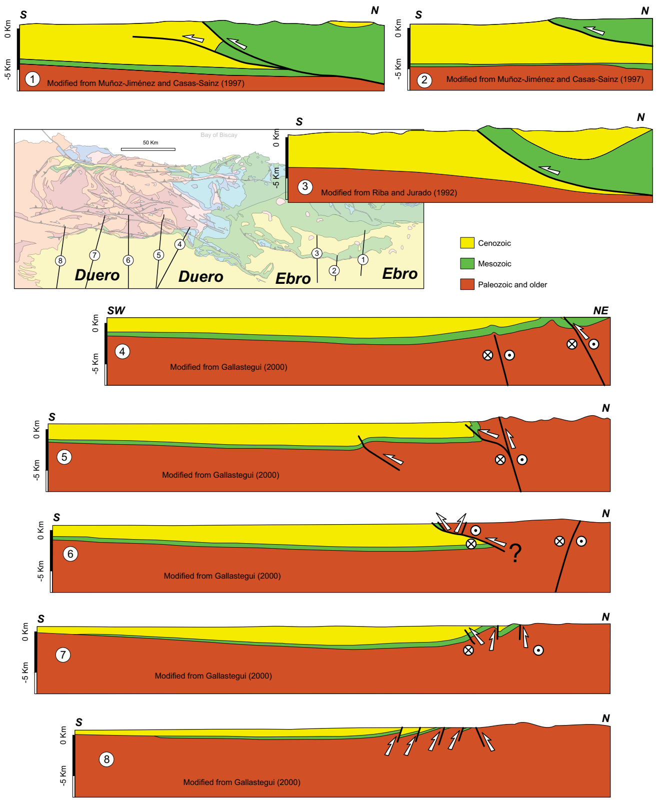

Fig. 5. Geological cross-sections across the mountain front of the study area.

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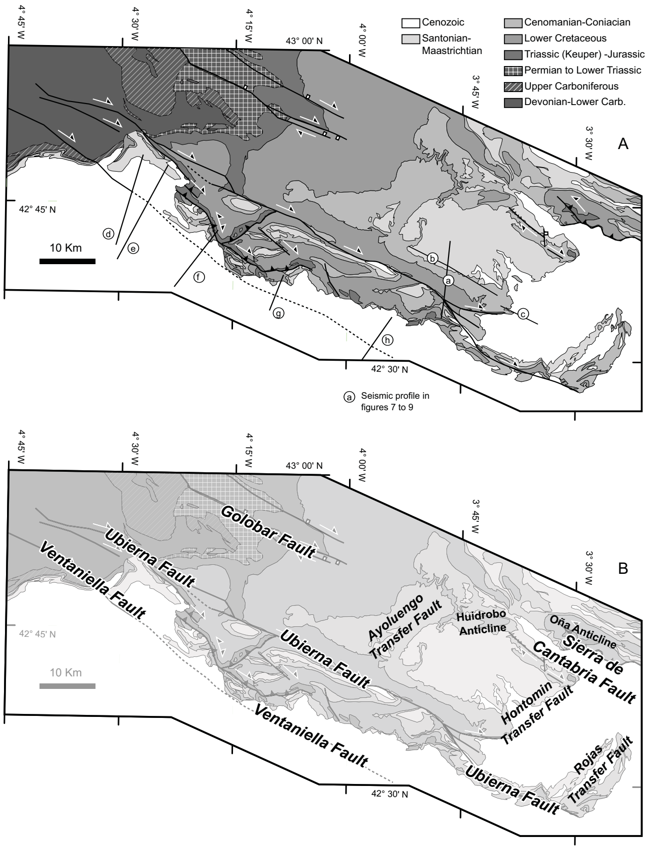

Fig. 6. (A) Geological map of the Plataforma Burgalesa Domain (modified from Tavani et al., 2011a), with traces of seismic lines. **(B)** Labelling of major faults.

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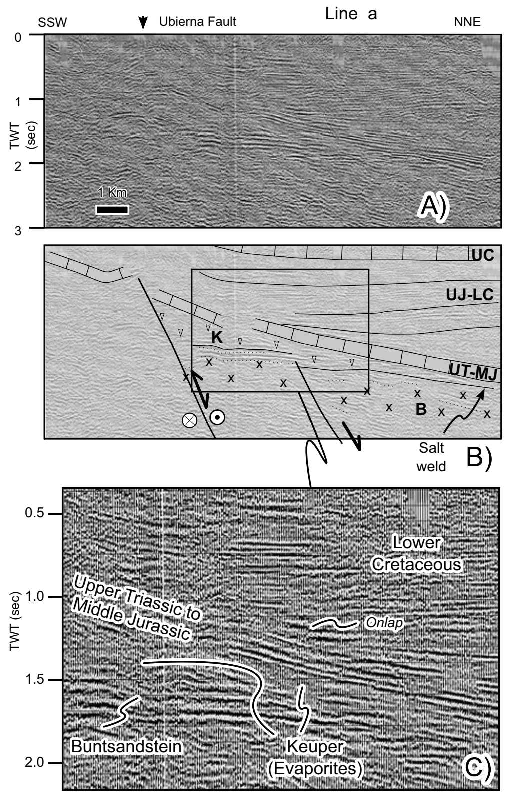

Fig. 7. **(A)** N–S striking seismic line a, with line-drawing **(B)** and detail illustrating the relationships between cover, evaporites and basement **(C)**. Hereafter C is Cenozoic; UC is Upper Cretaceous; UJ-LC is syn-rift upper Jurassic to lower Cretaceous; UT-MJ is pre-rift upper Triassic to middle Jurassic; K is keuper evaporites; B is basement.

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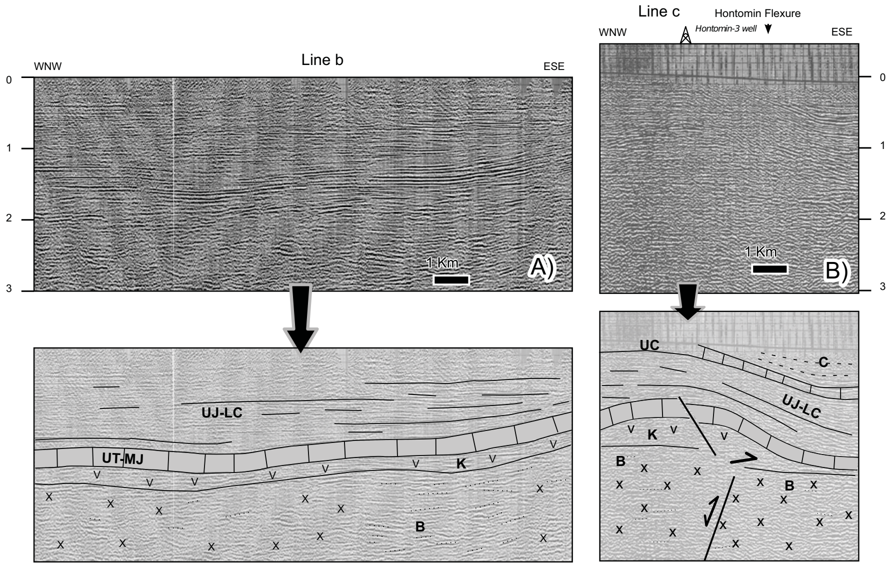

Fig. 8. WNW-ESE striking seismic lines b **(A)** and c **(B)**, with corresponding line-drawing.

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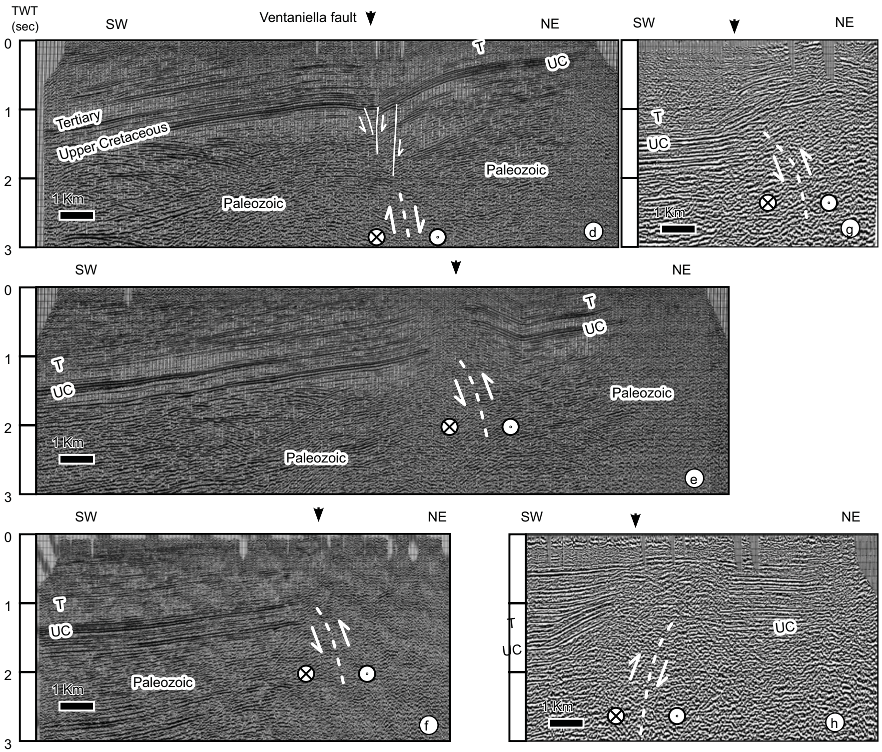

Fig. 9. Seismic lines crossing the Ventaniella Fault in the Duero Basin.

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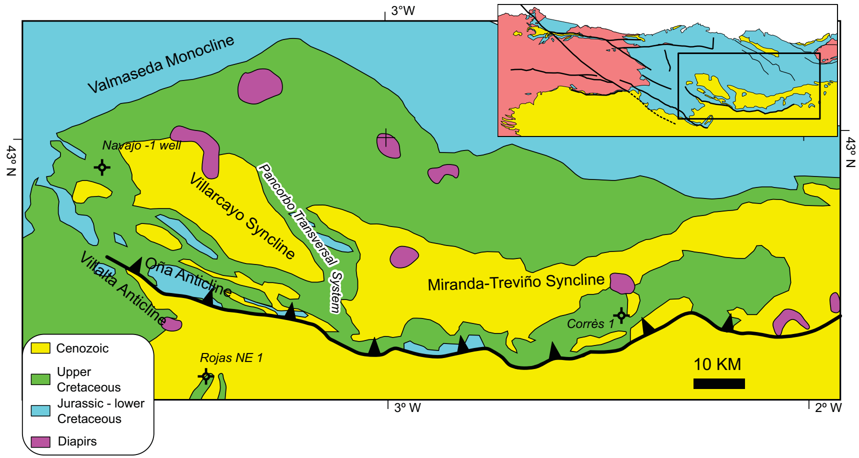

Fig. 10. Geological map of the southern portion of the Basque Pyrenees.

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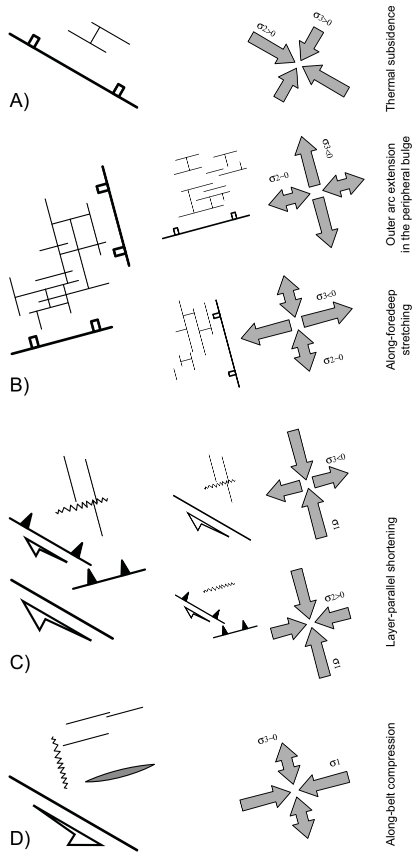

Fig. 11. Fracture patterns, stress fields and associated tectonic events recognised in the upper Cretaceous limestones of the Plataforma Burgalesa Domain and of the Villarcayo Syncline, after Quintà and Tavani (2012). See text for details.

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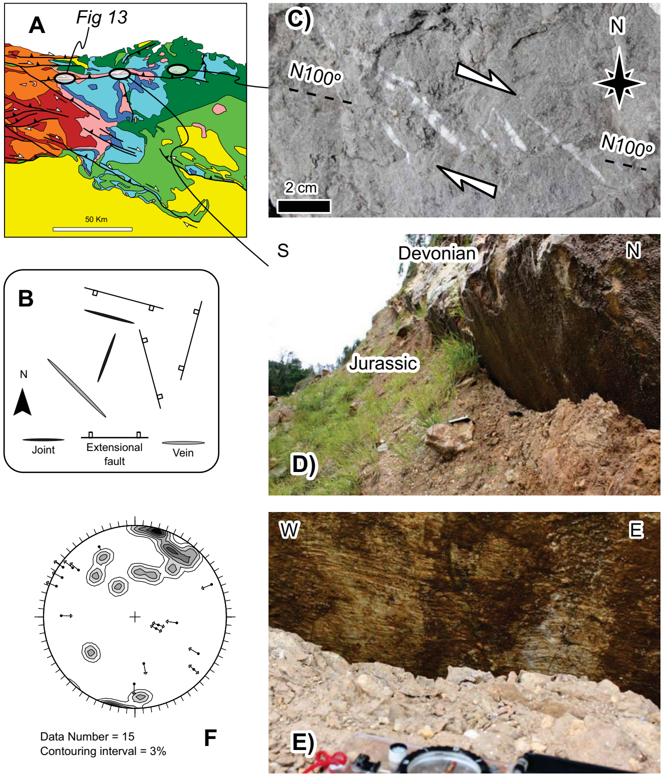

Fig. 12. (A) Geological map of the Cabuerniga Fault area. **(B)** Schematic map view of mesostructural patterns recognised in the area by Tavani and Muñoz (2012). **(C)** Detail of NW-SE striking en echelon veins, consistent with a E–W oriented right-lateral motion. **(D)** Photo of the tectonic contact between Devonian rocks and Jurassic marls along the central portion of the Cabuerniga Fault, with detail of right-lateral slickenlines **(E)** and stereoplot of mesofaults in the northern damage zone of the fault **(F)**.

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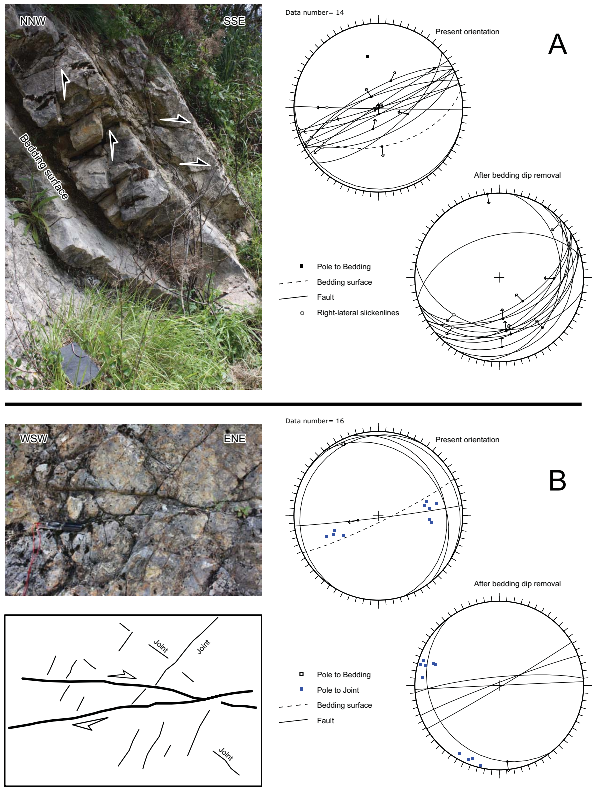

Fig. 13. Mesostructures and corresponding stereoplots of two outcrops in the southern block of the Cabuerniga Fault near its western termination. **(A)** tilted reverse faults. **(B)** Tilted right-lateral fault system postdating an earlier extensional system formed by two sets of mutually perpendicular joints.

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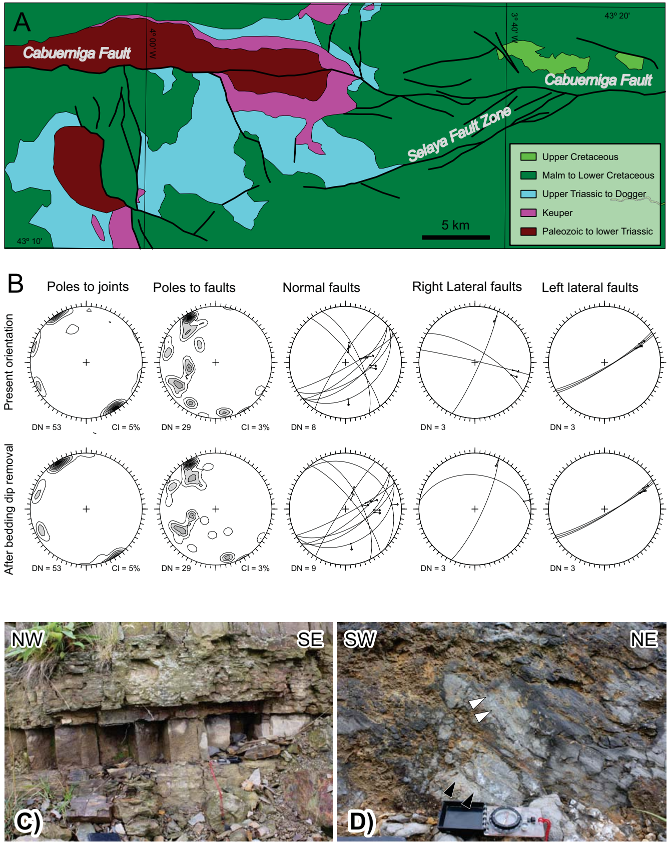

Fig. 14. (A) Geological Map of the Selaya Faut System. **(B)** Mesostructural data collected along the north-eastern termination of the fault system. **(C)** Bedding-perpendicular orthogonal joint sets. **(D)** Detail of a SW-NE striking almost dip-slip extensional fault (white arrows) later reactivated as a left-lateral transtensive element (black arrows).

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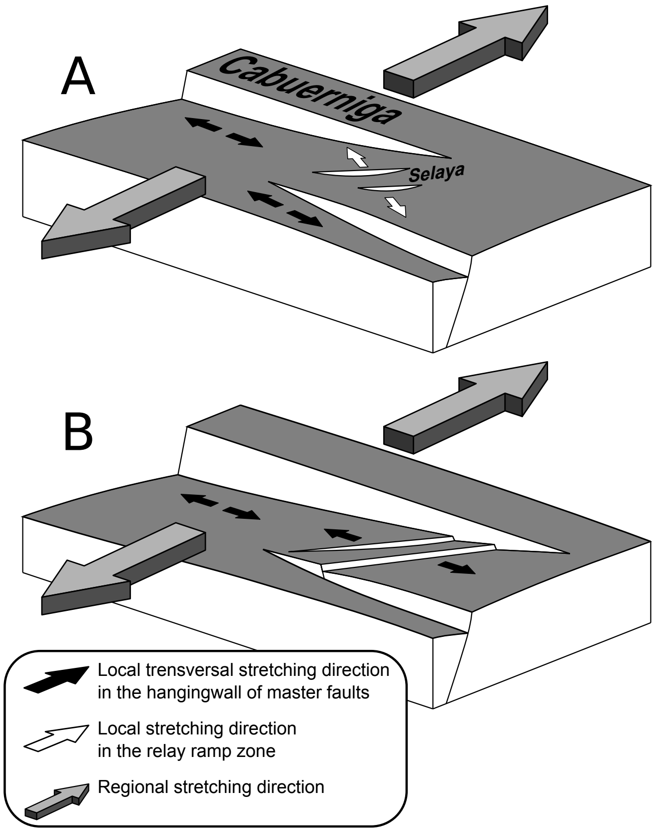

Fig. 15. 3-D block diagram showing the evolution of the Selaya Fault System.

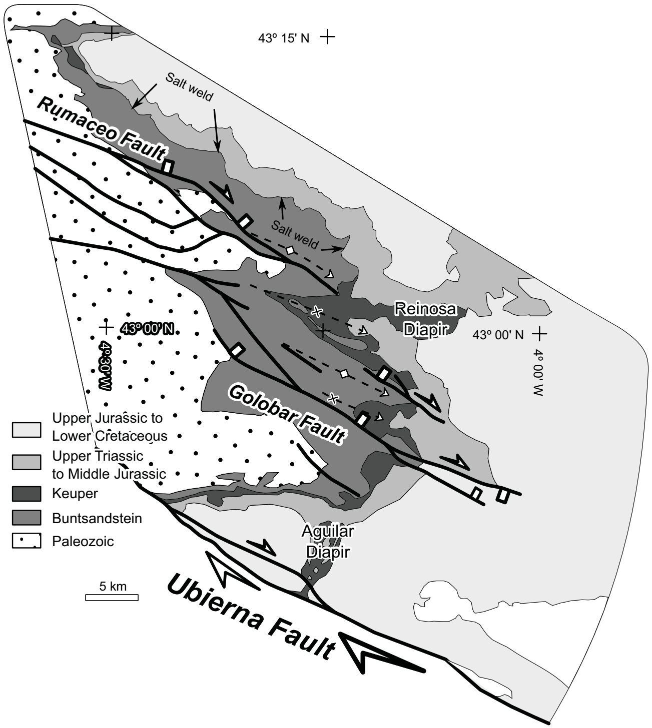

Fig. 16. Geological map of the Golobar and Rumaceo faults area.

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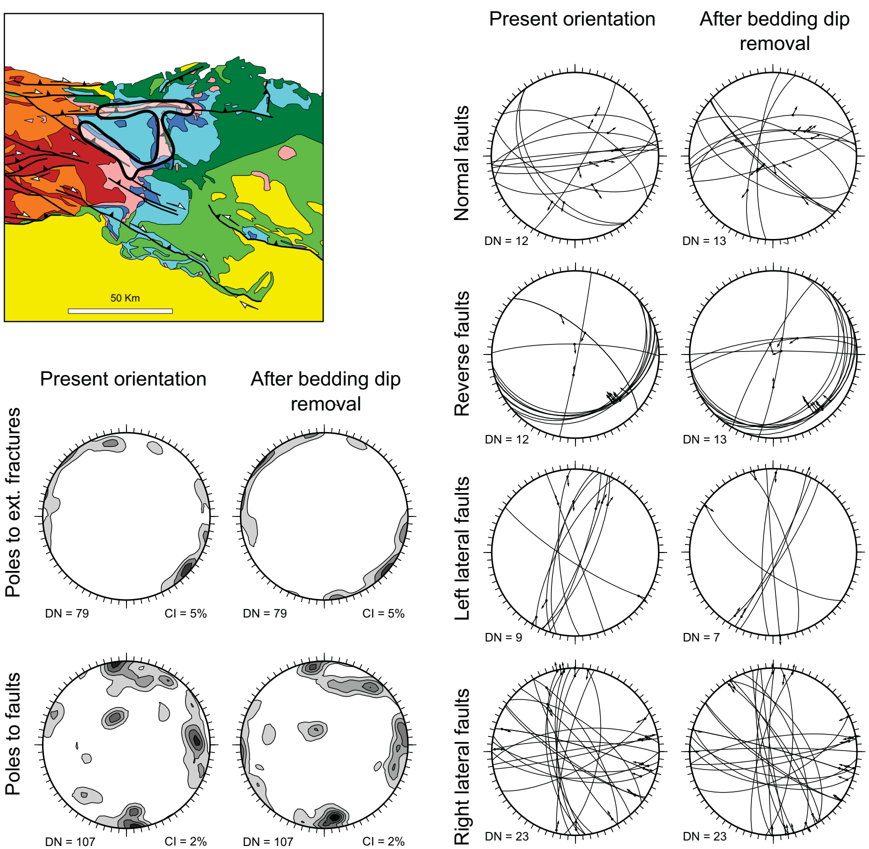

Fig. 17. Mesostructural data collected in the Permo-Triassic Buntsandstein facies.

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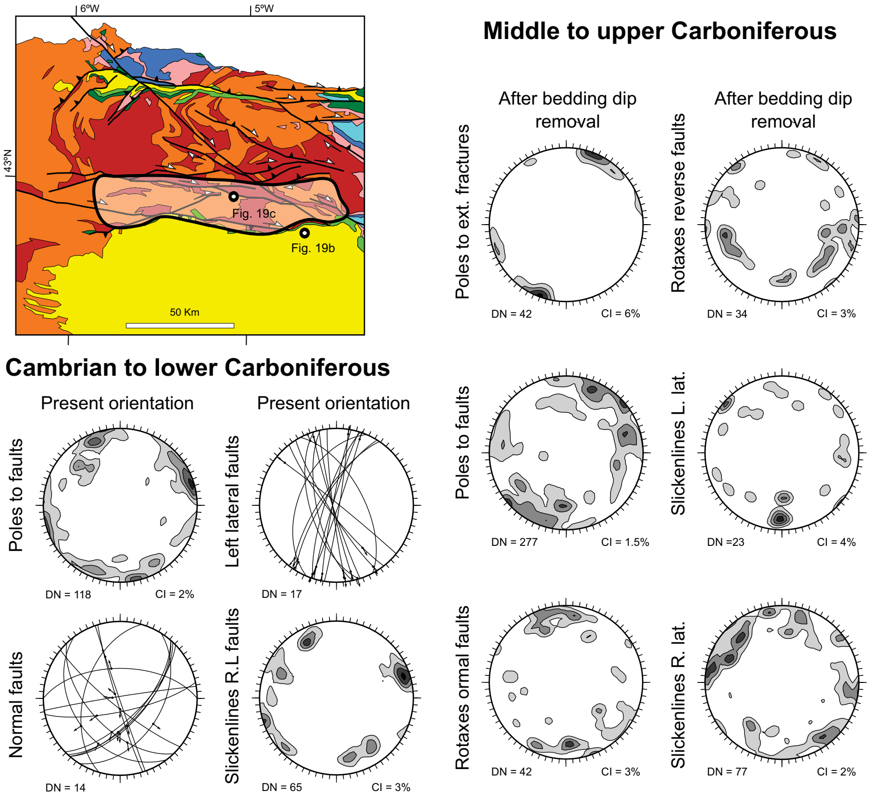

Fig. 18. Mesostructural data collected in Paleozoic rock of the Cantabrian Belt.

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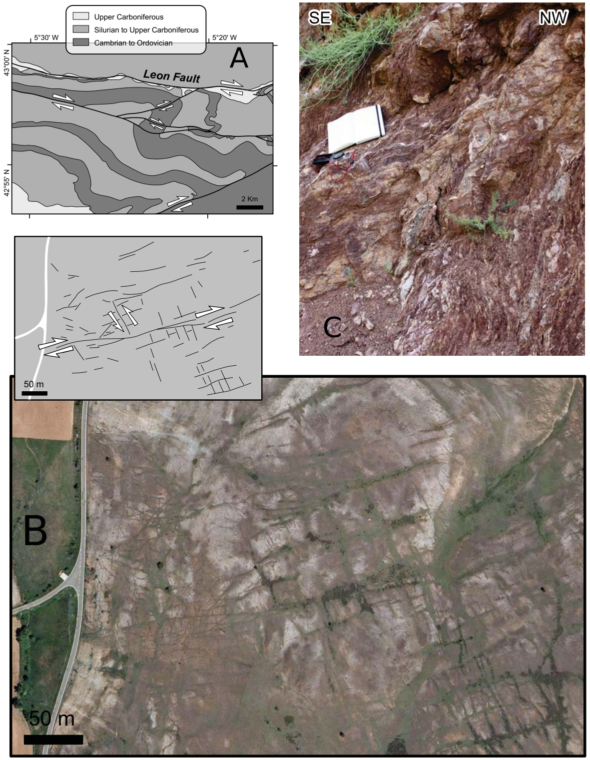

Fig. 19. (A) Schematic geological map in the area to the south of the Leon Fault. **(B)** Orthophoto and line-drawing of an area of the Duero Basin (see Fig. 18 for location) where sub horizontal Cenozoic layers are exposed. NNW-SSE and WSW-ENE striking fracture traces may corresponds to early-orogenic extensional assemblages, which have been documented to the east by Quintà and Tavani (2012). These are postdated by an about E–W striking fault, whose right-lateral kinematics is well-constrained by its antithetic left-lateral fault. **(C)** Right-lateral calcite slickenlines along a the Leon Fault System.

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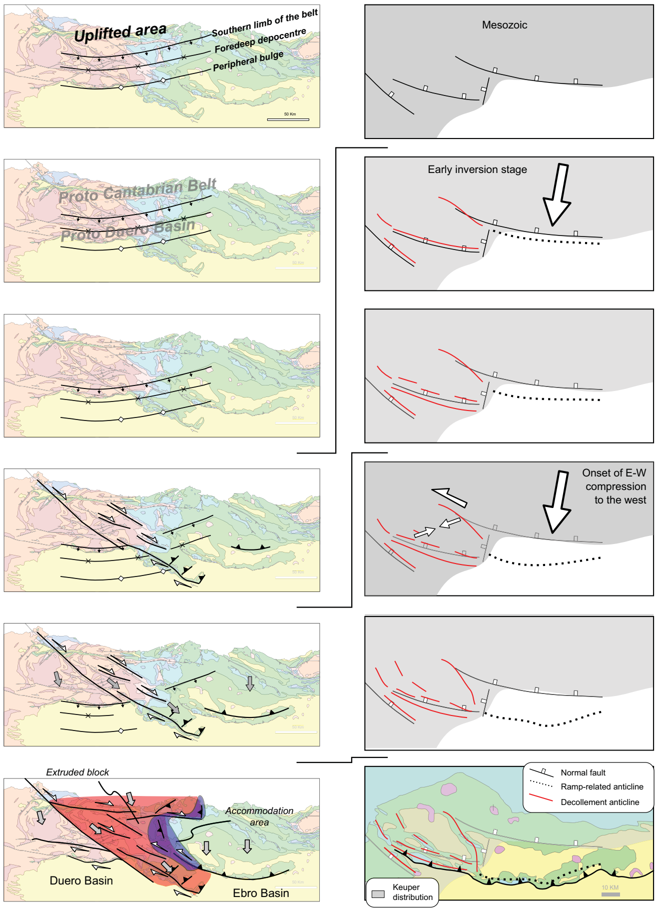

Fig. 20. Schematic Cenozoic evolution of the area (left), with detail of the Sierra de Cantabria Thrust Sheet (right).

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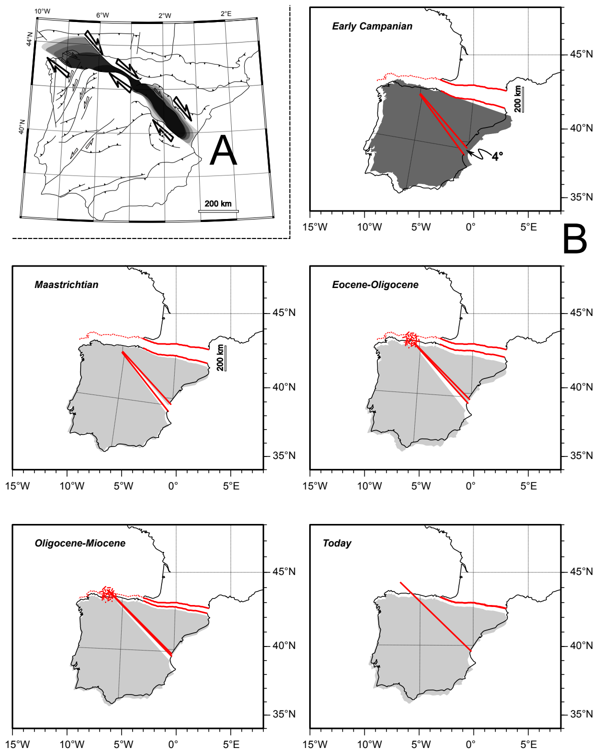

Fig. 21. (A) Tectonic sketch map of Fig. 1 showing the Iberian Chain-Ubierna-Ventaniella fault corridor. Grey tones tentatively indicate the amount of cumulative displacement. **(B)** Position of Iberia with respect to fixed Europe for five stages, from the latest Cretaceous to present. Dark grey area in the fist stage corresponds to the position of unbroken Iberia computed by Vissers and Meijer (2012). Light grey corresponds to the position of Iberia in the previous stage.

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