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CRUSTAL STRUCTURE OF THE EASTERN BASQUE-CANTABRIAN ZONE – WESTERN PYRENEES: FROM THE CRETACEOUS HYPEREXTENSION TO THE CENOZOIC INVERSION

Estructura cortical del borde oriental de la Zona Vasco-Cantábrica – Pirineos occidentales: de la hiperextensión cortical cretácica a la inversión tectónica cenozoica

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Abstract: *We present a new crustal-scale transect of the eastern Basque-Cantabrian Zone, through the Cinco Villas Massif, the Leiza-Aralar Thrust System and the South-Pyrenean Zone. The restoration of this transect to its pre-shortening stage allows us to assess the architecture of the hyperextended domain and the style of the Alpine contractional deformation. During the Cretaceous, extension led to a hyperthinned crust with local mantle unroofing to the base of the eastern Basque-Cantabrian Basin. The mantle unroofing process was driven by a complex system of detachments putting into contact Mesozoic sediments in the hanging wall with mantle rocks in the footwall. At this stage, extensive fluid circulation caused serpentinization of the uppermost mantle body. Furthermore, the thermal anomaly created during the unroofing caused high temperature metamorphism of the overlying sediments of the Leiza detachment system and hydrothermalism in further basins. The Alpine convergence gave rise to the tectonic inversion of the Mesozoic basins. Tectonic structures inherited from the Cretaceous hyperextension played a major role in mountain building. The southward indentation of the European crust forced the northwards subduction of the Iberian crust and the basement-cover decoupling along the Triassic evaporites. Restoration of this section to the end of the extensional period enabled us to estimate a shortening of~90 km.*

Keywords: *Pyrenees, Basque-Cantabrian Zone, hyperextension, Alpine orogeny, mantle unroofing.*

Resumen: *En este trabajo se presenta un nuevo modelo de estructura cortical en el borde oriental de la Zona Vasco-Cantábrica, atravesando el Macizo de Cinco Villas, el sistema de cabalgamientos de Leiza-Aralar y la Zona Surpirenaica. La restauración de esta sección al estadio previo a la convergencia alpina permite establecer la arquitectura del dominio cortical hiperextendido Mesozoico y el estilo de la deformación compresiva posterior. Durante el Mesozoico, la deformación extensional asociada a la apertura del Golfo de Vizcaya dio lugar a la formación de dominios de corteza hiperextendida y a la exhumación parcial del manto bajo la Cuenca Vasco-Cantábrica oriental. El proceso de exhumación del manto se produjo por la acción de un complejo sistema de detachments extensionales que pusieron en contacto la cuenca cretácica en el bloque superior con el manto en su bloque inferior. En este estadio, la intensa circulación de fluidos a lo largo de estos detachments causó la serpentinización de la parte superior del cuerpo mantélico. Además, la anomalía térmica creada en este proceso, generó un metamorfismo de alta temperatura que afectó a los materiales mesozoicos localizados inmediatamente sobre el manto exhumado, así como hidrotermalismo en cuencas más alejadas de la aureola metamórfica. La orogenia Alpina dio lugar a la inversión de las cuencas mesozoicas, y las estructuras tectónicas heredadas de la etapa de hiperextensión cortical jugaron un papel determinante en la configuración de la estructura orogénica. La indentación hacia el sur de la corteza Europea en la corteza Ibérica forzó la subducción de esta última hacia el norte y el desacoplamiento del basamento con respecto a la cobertera sedi-*

mentaria mesozoico-terciaria a lo largo del nivel de despegue de las evaporitas del Triásico superior. La restauración de esta sección cortical al final del periodo extensional indica un acortamiento cenozoico de aproximadamente 90 km.

Palabras clave: *Pirineos, Zona Vasco-Cantábrica, hiperextensión, orogenia Alpina, exhumación del manto.*

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Introduction

The Pyrenean-Cantabrian mountain chain extends along the northern border of Spain for 1,000 km in an east-west direction. It resulted from the convergence of Iberia and Eurasia between the Late Cretaceous and the Miocene, in the context of the Alpine orogeny (*e.g.*, Choukroune and ECORS Team, 1989; Muñoz, 1992; Vergés *et al.*, 1995; Rosenbaum *et al.*, 2002; Teixell *et al.*, 2018). Throughout most of the Mesozoic, this area was affected by lithospheric extension. This episode gave rise to the Bay of Biscay, in relation to the opening of the North-Atlantic Ocean, and deep basins formed in the Pyrenean realm (*e.g.*, Ziegler, 1988; García-Mondéjar *et al.*, 1996; Tugend *et al.*, 2014, 2015; Pedreira *et al.*, 2015). Around the SE corner of the present-day Bay of Biscay, the Basque-Cantabrian Basin developed as one of the most subsident basins of the Iberian periphery in the Aptian-Cenomanian (Rat, 1988; García-Mondéjar *et al.*, 1996).

For the Mesozoic, the overall kinematic evolution of Iberia relative to Europe has yielded to an intense debate in recent literature (*e.g.*, Barnett-Moore *et al.*, 2016, 2017, 2018; van Hinsbergen *et al.*, 2017; Nirrengarten *et al.*, 2018). To date, three models have been proposed: 1) a transtensional eastward motion of Iberia (*e.g.,* Olivet, 1996); 2) a Late Jurassic-Early Cretaceous strike-slip motion followed by near orthogonal extension (Jammes *et al.*, 2009; Nirrengarten *et al.*, 2017, 2018); and 3) a scissor-style opening of the Bay of Biscay coupled with subduction in the Pyrenean realm (Sibuet *et al.*, 2004; Vissers *et al.*, 2016). Within the context of this debate on the large-scale plate tectonics framework, different models were also proposed to explain the specific formation of the Basque-Cantabrian Basin. In the eastern part of this basin, previous works based on paleomagnetic, structural and stratigraphic data (García-Mondéjar *et al.*, 1996; Larrasoaña *et al.*, 2003a) suggested that the Iberian-European plate boundary in the Aptian-Albian was made up of pull-apart basins and basement blocks bounded by transverse structures that suffered rotations within a general context of left-lateral displacements. Subsequent studies focused on the presence of large-scale extensional detachment faults, outcrops of lower crust and mantle rocks in relation to those detachments, and the tectono-sedimentary architecture of the Cretaceous basins of the Pyrenean domain (*e.g.*, Jammes *et al.*, 2009; Lagabrielle *et al.*, 2010; Masini *et al.*, 2014). These studies suggested the formation of hyperextended rift systems by near orthogonal extension from the late Aptian onwards, creating domains of hyperthinned crust with local mantle unroofing in the Basque-Cantabrian Basin and other basins along the North-Pyrenean Zone (Lagabrielle *et al.*, 2010; Clerc *et al.*, 2013; Tugend *et al.*, 2014; Teixell *et al.*, 2016; DeFelipe *et al.*, 2017). In these domains, low-angle detachment faults overlying exhumed mantle are covered by synrift and postrift sediments (Manatschal, 2004; Lagabrielle and Bodinier, 2008; Masini *et al.*, 2014), and usually sole into a ductile lithostratigraphic unit that corresponds to Upper Triassic evaporites (Jammes *et al.*, 2009, 2010a). Unroofed and serpentinized mantle was also interpreted to be present in parts of the Bay of Biscay (Roca *et al.,* 2011; Tugend *et al.*, 2014; Fernández-Viejo *et al.*, 2012; Pedreira *et al.*, 2015). The Pyrenean-Cantabrian rift systems were strongly segmented by transfer zones, yielding to significant along-strike structural and stratigraphic differences (Jammes *et al.*, 2009, 2010b; Roca *et al.*, 2011; Masini *et al.*, 2014; Tugend *et al.*, 2014).

During the Cenozoic, the Alpine orogeny resulted in the inversion of the Mesozoic basins, leading to a continent-continent collision in the Pyrenees (*e.g.*, Muñoz, 1992; Beaumont *et al.*, 2000) and uplift of the Mesozoic passive margin further west, creating a coastal range (the Cantabrian Mountains) (Alonso *et al.*, 1996; Pulgar *et al.*, 1996; Gallastegui *et al.*, 2002; Pedreira *et al.*, 2015; Quintana *et al.*, 2015). In this context, the Basque-Cantabrian Basin was also uplifted and incorporated into the Pyrenean-Cantabrian mountain chain, forming the Basque-Cantabrian Zone (Fig. 1). Several works have been carried out on the crustal-scale structure of the Pyrenean-Cantabrian mountain chain; specially in the central and western Pyrenees and in the central Cantabrian Mountains, where deep seismic surveys helped to constrain the tectonic evolution more precisely (*e.g.*, Choukroune and ECORS Team, 1989; Roure *et al.*, 1989; Muñoz, 1992; Daignières *et al.*, 1994; Pulgar *et al.*, 1996; Teixell, 1998; Beaumont *et al.*, 2000; Pedreira *et al.*, 2003, 2007, 2015; Gallastegui *et al.*, 2016; Teixell *et al.*, 2016, 2018). Along the whole belt, the Iberian plate subducts to the north, with the European plate indenting into the Iberian crust, although along-strike differences are highlighted in terms of the structure of the inverted basins, the reactivation of inherited faults and the amount of inferred crustal shortening. Analyzing the crustal-scale structure of the orogen along different transects, from the Pyrenees to the Cantabrian Mountains, has become a major aim in recent years in order to gain insight into the 3D geometry of the former rift systems (Lagabrielle *et al.*, 2010; Jammes *et al.*, 2010b; Roca *et al.*, 2011; Masini *et al.*, 2014; Hart *et al.*, 2017; Teixell *et al.*, 2018).

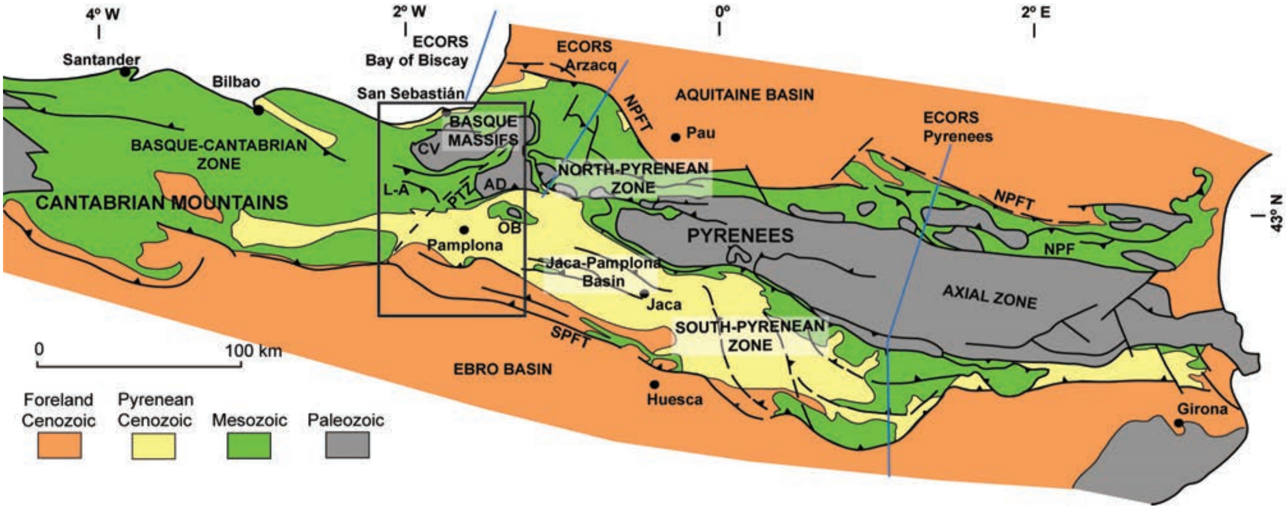

Fig. 1.- Schematic tectonic map of the Pyrenees and the eastern Cantabrian Mountains. The black rectangle marks the studied area (see Fig. 2). The blue lines show the location of the ECORS seismic reflection profiles. L-A: Leiza-Aralar Thrust System; PTZ: Pamplona Transfer Zone; CV: Cinco Villas Massif; AD: Alduides Massif; OB: Oroz-Betelu Massif; NPFT: North-Pyrenean Frontal Thrust; SPFT: South-Pyrenean Frontal Thrust; NPF: North-Pyrenean fault (after Teixell, 1998).

Regarding the Basque-Cantabrian Zone, previous structural works studied mainly the Aptian-Albian tectonic pattern (García-Mondéjar *et al.*, 1996; Iriarte, 2004) and the Alpine tectonic inversion but without deep geophysical data (Turner, 1996; Cámara, 1997; Gómez *et al.*, 2002; Larrasoaña *et al.*, 2003a, b; Martínez-Torres, 2008). A seismic refraction/wide-angle reflection survey carried out in 1997 (Pedreira *et al.*, 2003) provided some information that allowed the crustal-scale reconstruction of the Alpine orogeny in the central Basque-Cantabrian Zone as described by Pedreira (2005), Pedreira *et al.* (2007) and Quintana *et al.* (2015). In this contribution, we present a crustal-scale transect of the easternmost part of the Basque-Cantabrian Zone, defined at depth by the same seismic dataset with additional inputs from more recent geophysical studies (Ruiz *et al.*, 2006a, b; Chevrot *et al.*, 2015).

Our main goal is to characterize the crustal-scale geological structure of the eastern Basque-Cantabrian Zone and to reconstruct this transect to the end of the maximum extensional period. Furthermore, we have examined the architecture of the hyperextended domain with mantle unroofing, the Cenozoic reactivation of rift-inherited structures and the amount of shortening during the Alpine orogeny.

Geological setting

The studied area is located in the transition zone between the Pyrenees and the Cantabrian Mountains, within the so-called Basque-Cantabrian Zone (Fig. 1). The boundary between these two zones has been traditionally located in the NNE-SSW trending Pamplona Transfer Zone (PTZ) (also known as Pamplona Fault; *e.g.*, Larrasoaña *et al.*, 2003b; DeFelipe *et al.*, 2017; Vacherat *et al.*, 2017) (pale grey band in Fig. 2). The PTZ is not clearly visible at the surface, but it can be traced by an alignment of Upper Triassic salts diapirs and shallow earthquake epicenters (Larrasoaña *et al.*, 2003b; Ruiz *et al.*, 2006b). It also marks significant lateral changes in the seismic velocity distribution of the whole crust (Pedreira *et al.*, 2003). The PTZ represents a paleogeographic and structural division that played a major role during the Cretaceous extension. It marks the eastern lateral boundary of the deep Cretaceous Basque-Cantabrian Basin (Rat, 1988; García-Mondéjar *et al.*, 1996) whereas to the east, the main Cretaceous depocenter is displaced towards the north, in the Arzacq-Mauléon Basin (*e.g.*, Larrasoaña *et al.*, 2003b; Masini *et al.*, 2014; Vacherat *et al.*, 2017). During the Alpine orogeny, this tectonic transfer zone was inherited and partitioned also the compressional deformation: east of the PTZ, all major structures are south-vergent, whereas in the western block several north-vergent thrusts are present.

One of the most distinctive features in this area is the presence of basement outcrops forming the so-called Basque Massifs: Cinco Villas, Alduides and Oroz-Betelu (Fig. 2). These massifs are made up of Ordovician to Permian rocks (Del Valle *et al.*, 1973; Campos, 1979; Velasco *et al.*, 1987). The Mesozoic cover begins with the Lower Triassic red sandstones of the Buntsandstein facies (Campos, 1979; Diez *et al.*, 2005) that crop out at the limits of the Basque Massifs. The Middle Triassic Muschelkalk facies hardly crops out and the Upper Triassic Keuper facies evaporites appear in diapirs and along thrusts and anticlines. The Keuper facies evaporites are frequently intruded by Upper Triassic to Lower Jurassic sub-volcanic basic rocks (known as ophites) (Rossy *et al.*, 2003; González *et al.*, 2007). Jurassic rocks crop out in E-W-trending bands south of the Cinco Villas Massif and in basins at the NW of this massif. Jurassic rocks are mainly limestone and marls deposited in shallow-open platforms (Bádenas, 1996; Aurell *et al.*, 2003). Cretaceous rocks can be grouped in three units: 1) the Purbeck-Weald complex (uppermost Jurassic-Barremian), formed by sandstones and limestones (Rat, 1988); 2) the Urgonian complex (Aptian to early Cenomanian), formed by marls and limestones (*e.g.*, Rat, 1988; García-Mondéjar *et al.*, 1996; Bodego *et al.*, 2015 and references therein); and 3) Upper Cretaceous flysch sedimentation (Rat, 1988; Mathey *et al.*, 1999; Brusset *et al.*, 1997; Tilhac *et al.*, 2013). Cenozoic rocks crop out in a narrow band

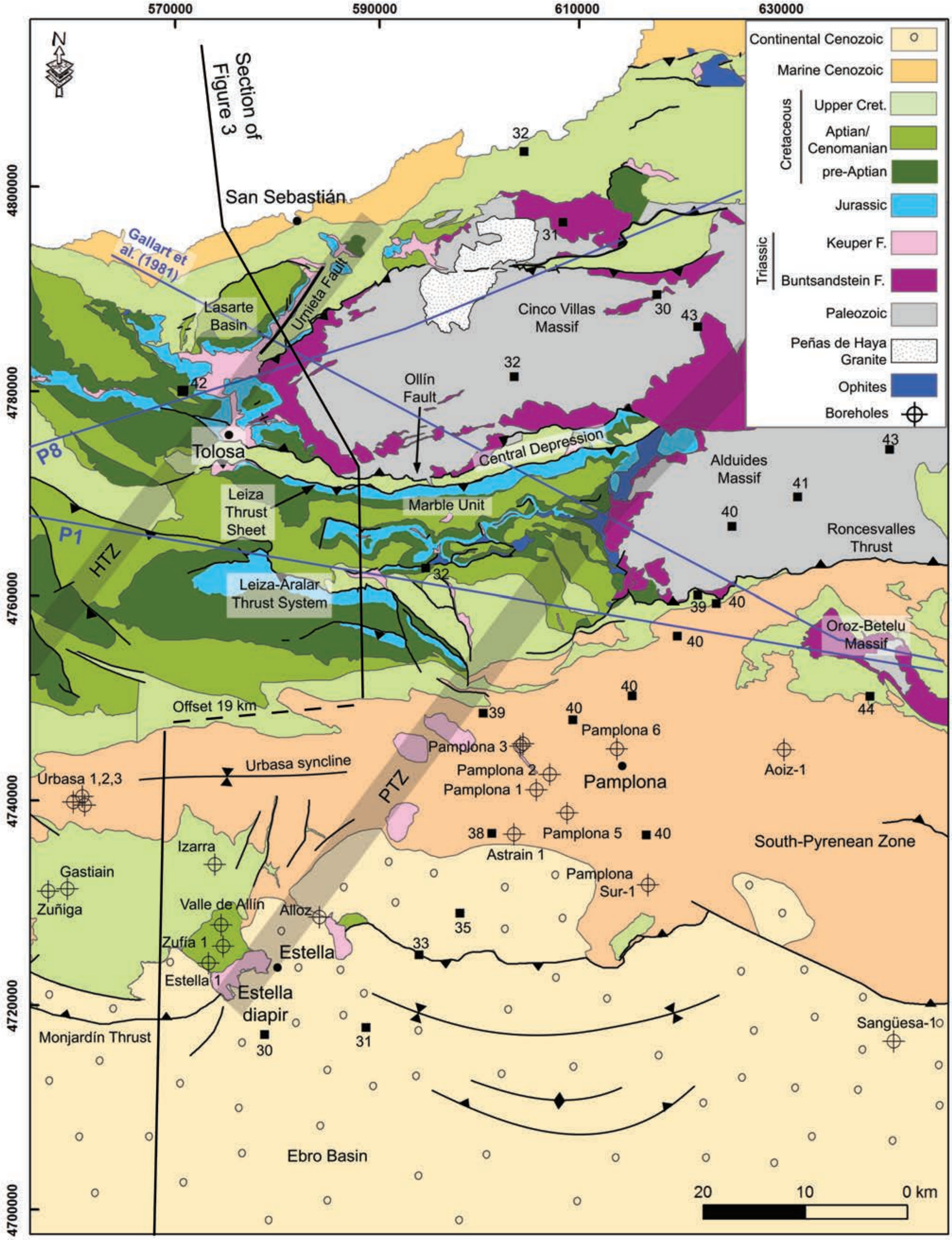

Fig. 2.- Geological map of the studied area (see location in Fig. 1). The boreholes are taken from Lanaja (1987) and the black squares represent the Moho depth according to Díaz *et al.* (2012) and Chevrot *et al.* (2015). P1 and P8 are the geophysical profiles by Pedreira *et al.* (2003) and Pedreira (2005). The E-W seismic refraction profile by Gallart *et al.* (1981) is drawn. The pale grey bands show the location of the Pamplona and Hendaya Transfer Zones (PTZ and HTZ, respectively). Geological mapping modified from the IGME 1:50,000: Campos *et al.*, 1972a, b; Campos and García-Dueñas, 1972; Knausse *et al.*, 1972; Juch *et al.*, 1972; Del Valle, 1972; Del Valle *et al.*, 1972, 1973; Puigdefábregas *et al.*, 1976; Carbayo *et al.*, 1972, 1977; Gabaldón *et al.*, 1983, 1984a, b, c, 1985; Ramírez Merino *et al.*, 1984; Ramírez *et al.*, 1986.

along the coast, in the western part of the South-Pyrenean Zone (traditionally called Jaca-Pamplona Basin) and in the Ebro Foreland Basin. Paleocene to lower Priabonian rocks are marls and shallow-water limestones (Payros *et al.*, 2007), while the upper Priabonian to Neogene materials are detrital sediments formed in a continental environment (Teixell and García-Sansegundo, 1995; Muñoz-Jiménez and Casas-Sainz, 1997).

There are several major structures in this area, including the North-Pyrenean Frontal Thrust, the Ollín Fault, the Leiza-Aralar Thrust System, the South-Pyrenean Frontal Thrust and the Pamplona and Hendaya Transfer Zones (Fig. 2). The North-Pyrenean Frontal Thrust is an E-W to NW-SE oriented north-vergent thrust that separates the North-Pyrenean Zone from the Aquitaine Basin. Towards the west, it is submerged in the Bay of Biscay. The Ollín Fault runs along the southern border of the Cinco Villas Massif. This fault cannot be mapped neither east of the PTZ nor west of another transfer zone, the so-called Hendaya Transfer Zone (or Hendaya Fault; Pedreira *et al.*, 2003, 2007; Ruiz *et al.*, 2006b), shown in Figure 2 as a pale grey band. The Ollín Fault superposes the Cinco Villas Massif over a narrow basin, the *Depression Intermediare* or Central Depression (Lamare, 1936; Iriarte, 2004). This basin shows evidence of hydrothermalism with temperatures of < 185 ºC (Iriarte, 2004; Iriarte *et al.*, 2011). The Leiza-Aralar Thrust System is located south of the Central Depression and is formed by a series of north-vergent thrust sheets. Every thrust sheet carries Upper Triassic to Lower Cretaceous rocks in its hanging wall. The northern part of the Leiza-Aralar Thrust System shows evidence of high temperature metamorphism, called *Nappe des Marbres* or Marble Unit (Lamare, 1936). Maximum metamorphic temperatures are estimated at 500 to > 550 ºC (Martínez-Torres, 2008; Ducoux *et al.*, 2018) close to the Leiza thrust sheet (the northernmost sheet of the Leiza-Aralar Thrust System). Towards the south, the metamorphic grade decreases progressively. Along the Leiza thrust sheet, fragments of the Paleozoic basement and high-grade metamorphic rocks crop out (Mendia and Gil Ibarguchi, 1991). Specifically, in the junction between the Leiza thrust sheet and the PTZ, the Ziga *mélange* crops out. This *mélange* is made up of a clayey-evaporitic matrix with Keuper facies affinities, embedding fragments of peridotites, granulites, marbles and Mesozoic (meta)sedimentary rocks (DeFelipe *et al.*, 2017). The South-Pyrenean Frontal Thrust has an E-W to ESE-WNW orientation and superposes the South-Pyrenean Zone and the Basque-Cantabrian Zone over the Ebro Foreland Basin. It is locally buried under post-tectonic Cenozoic sediments. In the intersection of the South-Pyrenean Frontal Thrust and the PTZ, the Estella diapir includes blocks of lower crustal and Mesozoic (meta)sedimentary rocks (Pflug, 1973).

Geological cross-section

A geological cross-section has been constructed to characterize the easternmost Basque-Cantabrian Zone (Fig. 3). It runs from the Bay of Biscay to the Ebro Foreland Basin with a N-S and NNW-SSE orientation in order to cut the main structures as orthogonally as possible. There is an offset of 19 km south of the Leiza-Aralar Thrust System to avoid the structural and stratigraphic changes across the Pamplona Transfer Zone. The cross-section has been constructed based on own field data, published geological maps (at scale 1:50,000 from Serie Magna IGME and at scale 1:25,000 from *Gobierno de Navarra* and *Ente Vasco de la Energía*), borehole data (Lanaja, 1987) and published cross-sections (Muñoz-Jiménez and Casas-Sainz, 1997; Larrasoaña *et al.*, 2003b; Iriarte, 2004; Bodego and Agirrezabala, 2013). The area studied has been divided into three geographical sectors.

Northern Sector

The northern sector comprises the structures located north of the Ollín Fault. In this sector what crops out are the Paleozoic rocks of the Cinco Villas Massif and their Lower Triassic cover, the mid-Cretaceous Lasarte Basin, the flysch deposits of the Upper Cretaceous and the Paleocene. The Ollín Fault is a south-vergent thick-skinned fault that exhumes the Cinco Villas Massif, which shows an overall antiformal structure. This massif was covered by Mesozoic and Cenozoic -currently eroded- sediments (Fig. 3). A low-temperature thermochronological study in the Carboniferous rocks of the western part of the Cinco Villas Massif, points to a fast cooling during the late Eocene-Oligocene and an exhumation of more than 7 km (DeFelipe *et al.*, 2018b). The Lasarte Basin is located at the NW border of the Cinco Villas Massif. It is limited by the Urnieta Fault, considered to be the surface expression of the geophysically defined Hendaya Transfer Zone (Pedreira *et al.*, 2003; Ruiz *et al.*, 2006b). This basin is filled by Jurassic to Lower Cenomanian sediments. The structure in this area consists of folded sub-basins separated by high-angle faults (Bodego and Agirrezabala, 2013; Bodego *et al.*, 2015). The north-vergent North-Pyrenean Frontal Thrust has been delineated based on bibliographic data from the ECORS-Bay of Biscay seismic profile (Bois *et al.*, 1997) and the seismic reflection MARCONI-3 profile (Ferrer *et al.*, 2008). Bois *et al.* (1997) described the stratigraphy of the Cantabrian shelf as formed by a thin Triassic-Lower Jurassic series unconformably overlaid by Upper Cretaceous and Eocene flysch deposits.

Central Sector

The central sector comprises the structures located between the Ollín Fault and the South-Pyrenean Frontal Thrust: the Central Depression, the Leiza-Aralar Thrust System and the Urbasa syncline.

The Central Depression is located between the Ollín Fault and the Leiza thrust sheet. It is a narrow basin with Upper Cretaceous sediments cropping out in its central and western parts (Iriarte, 2004; Bodego *et al.*, 2015) and forms a tight syncline. This basin is thrust at both margins. Specifically, we interpret that it is largely thrust by the Leiza-Aralar Thrust System, juxtaposing units with very different thermal evolution: high-temperature metamorphism at > 500 ºC in the south (Marble Unit) and punctual hydrothermal activity at < 200 ºC in the north (Central Depression).

The Leiza-Aralar Thrust System is formed by five north-vergent thrust sheets detached from the Upper Triassic evaporites. Each thrust sheet carries Upper Triassic to Cretaceous materials in its hanging wall. The general structure is formed by tight anticlines and broad synclines. The Leiza thrust sheet was exhumed progressively during the late Eocene-Oligocene, largely overthrusting the Central Depression. Slightly afterwards, the Ollín Fault superposed the Cinco Villas Massif over the Central Depression and the Marble Unit, as suggested by low-temperature thermochronological ages (DeFelipe *et al.*, 2018b) and the folding and overturning of the north-vergent structures in the footwall of the Ollín Fault (Martínez-Torres, 2008). The Upper Triassic decollement level of the Leiza-Aralar Thrust System represents the upper surface of a southward-directed indenting wedge of basement and cover rocks, whose southern structure is the so-called Urbasa Thrust (Fig. 3). This indenting wedge also forced the tilting of the Mesozoic beds on top of it, forming the northern limb of the Urbasa syncline.

The Urbasa syncline is a broad structure with Cenozoic rocks in its hinge zone. The existence of several boreholes in this area has made it possible to measure the significant Lower Cretaceous cover that thickens towards the south. This sub-basin is limited to the south by the South-Pyrenean Frontal Thrust, known in this part of the mountain chain as the Monjardín Thrust (or Villamayor de Monjardín-Etayo-Mirafuentes Thrust; Riba Arderiu, 1992).

Southern Sector

The southern sector comprises the Cenozoic continental sediments of the Ebro Foreland Basin, known in this part of the Pyrenean-Cantabrian mountain chain as the Rioja Trough. It is an E-W elongated trough filled with coarse sediments in the northern and southern borders and fine deposits in the central part (Muñoz-Jiménez and Casas-Sainz 1997; Inglès *et al.*, 1998). The sedimentary thickness of the continental Cenozoic deposits in the Rioja Trough has been estimated between 4.5 and 5 km (Muñoz-Jiménez and Casas-Sainz, 1997; Larrasoaña *et al.*, 2003b). Below this cover, Mesozoic to Eocene materials reduce their thicknesses progressively towards the south (Larrasoaña *et al.*, 2003b). The stratigraphic sequence of the northern margin of the Rioja Trough forms a monocline in the hanging wall of a blind thrust (Muñoz-Jiménez and Casas-Sainz 1997). This hanging wall monocline is cut by the Monjardín Thrust. Detailed mapping of this monocline structure was carried out by Riba Arderiu (1992) who described its northern flank as almost vertical or even inverted, thus forming an uppermost Oligocene angular unconformity. Larrasoaña *et al.* (2003b) estimated 14.6 km of shortening for the south Pyrenean basal thrust in a N-S cross-section located approximately 15 km west of the Estella diapir.

A crustal-scale model of the eastern Basque-Cantabrian Zone

Figure 4a shows the crustal-scale model of the easternmost Basque-Cantabrian Zone based on available geophysical data. It has been constructed with the Moho depth data obtained from receiver functions (Díaz *et al.*, 2012; Chevrot *et al.*, 2015) and seismic refraction/wide-angle reflection profiles (Pedreira *et al.*, 2003, 2005). P-wave velocites have been extracted from the profiles 1 and 8 and have been superimposed in the intersection with our transect (see location of profiles in Fig. 2). Earthquake hypocenters (Ruiz *et al.*, 2006a, b) have been superimposed over this transect to image faults with recent activity.

At a crustal scale, the main feature is the subduction of the Iberian crust below the European crust, which is described in the Pyrenean-Cantabrian mountain chain (Roure *et al.*, 1989; Muñoz, 1992; Daignières *et al.*, 1994; Pulgar *et al.*, 1996; Teixell, 1998; Pedreira *et al.*, 2003; Quintana *et al.*, 2015; Teixell *et al.*, 2018). The architecture displayed in Figure 4a implies a basement-cover decoupling at the decollement level in the Upper Triassic evaporites, enhancing the indentation of the European wedge towards the south, into the Iberian crust. Three main thick-skinned faults stand out in the proposed transect. The Ollín Fault extends down to the base of the crust, at 30 km deep (DeFelipe *et al.*, 2018a), as per the alignment of recent hypocenters (Ruiz *et al.*, 2006b). In spite of the dimensions of this structure, the seismic refraction models indicate that the underthrusting of the Iberian plate takes place further south. Therefore, we interpret that the Urbasa Thrust represents the limit between the Iberian and European crusts. The Urbasa Thrust enhances the uplift observed in the

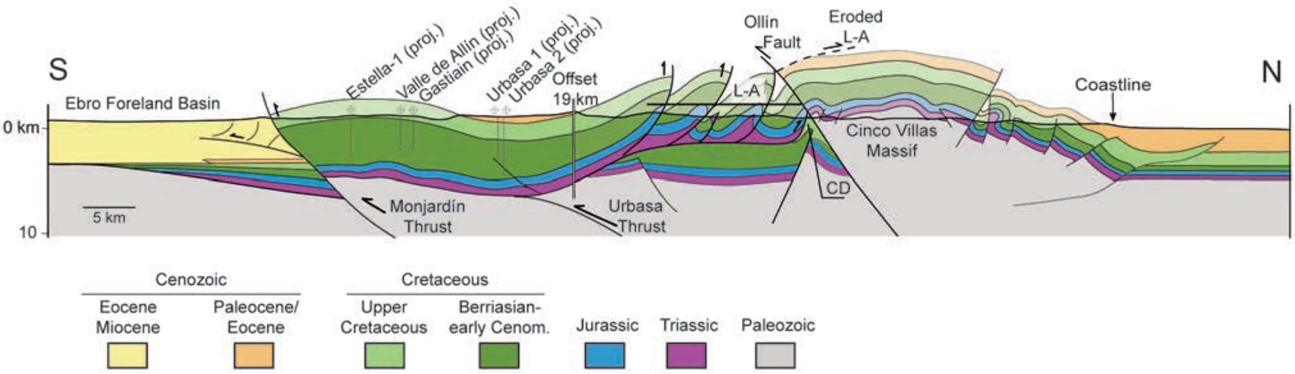

Fig. 3.- Geological cross-section of the eastern Basque-Cantabrian Zone (see location in Fig. 2). CD: Central Depression, L-A: Leiza-Aralar Thrust System.

Leiza-Aralar Thrust System with respect to the Cretaceous basin located southwards. Finally, the Monjardín Thrust, cutting the Iberian plate, connects with the South-Pyrenean Frontal Thrust at the surface.

P-wave velocities have been extrapolated from profiles 1 and 8 by Pedreira *et al.* (2003) and Pedreira (2005). Profile 1 intersects our transect in the Leiza-Aralar Thrust System, while profile 8 intersects our transect in the northwestern part of the Cinco Villas Massif. In the crustal-scale transect (Fig. 4a), representative P-wave velocities have been indicated as numbers in grey boxes. Profile 1 shows typical upper-middle crustal P-wave velocities of 6-6.35 km/s reaching a depth of 35 km, and velocities of 7.35-7.4 km/s at a depth of 35 to 45 km. Velocities in this deeper layer are anomalous in the sense that they are intermediate between typical lower crustal velocities (6.80-7.20 km/s) and typical upper mantle velocities (7.90-8.20 km/s). Profile 8 presents the northward subduction of the Iberian plate. The European crust P-wave velocities increase from ~6.00 to 6.20 km/s in the upper-middle crust, with velocities of 7.2 km/s in the lower crust. P-wave velocities in the deepest part of the Iberian crust are, again, of 7.4-7.45 km/s. Therefore, both profiles evidence the presence of a body of anomalous P-wave velocities (7.35-7.45 km/s) in the deepest part of the Iberian crust. We interpret these P-wave velocites as mantle serpentinized during the Albian, when peridotites were unroofed reaching the base of the eastern Basque-Cantabrian Basin (DeFelipe *et al.*, 2017). The absence of velocities typical for the lower crust on top of this layer may be explained by the substractive effect of the extensional detachments during the Mesozoic. Gabbroic instrusion on lower crustal materials, a common process in hyperthinned domains, could explain the P-wave velocities registered for the lower European crust in Profile 8 (7.2 km/s; Pedreira *et al.*, 2003; Pedreira, 2005).

The seismicity pattern registered in the Cinco Villas Massif shows a north-dipping alignment of hypocenters from the southern border of the massif to the base of the crust. Focal mechanisms point to a normal fault, evidencing crustal readjustments after the cessation of the orogenic activity (Ruiz *et al.*, 2006b). South of the Cinco Villas Massif, the seismicity shows a more dispersed pattern (Ruiz *et al.*, 2006a, b). Shallow hypocenters are associated here with the Leiza-Aralar Thrust System, and deeper hypocenters may be associated with structures below the Central Depression and with the Urbasa and Monjardín faults.

Figure 4b shows a restoration of this transect to the end of the maximum extensional period. In our reconstruction, we will refer to 'unroofed domain' or 'unroofed mantle' whenever mantle rocks get into contact with the sedimentary basins. These terms do not imply any sea floor exposure of the mantle rocks.

At the end of the extensional stage (Fig. 4b), the crust was progressively thinned away from the continental margins and mantle rocks were unroofed in the deepest portion of the central basin. This crustal architecture was achieved by a complex system of detachments. We assume that the crust was thinned by independient systems of extensional faults, developed in the upper crust and in the lower crust and upper mantle, with a decoupling horizon in a mid-crustal ductile layer (Manatschal, 2004). As soon as the thinning factor was enough to promote brittle deformation in the whole crustal column, those shallow and deep systems were connected, allowing fluids to circulate from the surface to the upper mantle, causing the serpentinization of the peridotites. At a first stage, the Monjardín Fault was connected to the main north-dipping detachment at depth, but as soon as extension progressed, the deformation was also accomodated by the Leiza detachment system, connected at depth with the main south-dipping detachment. The serpentinization of the unroofed upper mantle body between these two opposite vergent detachment zones caused the decrease of the P-wave velocities. Further evidence of mantle unroofing is the presence of serpentinized peridotites with ophicalcite in the Ziga *mélange* (DeFelipe *et al.*, 2017), brought to the surface by the Cenozoic inversion of the Leiza detachment system. Furthermore, the thermal anomaly created by the mantle unroofing, yielded to the Cretaceous high temperature metamorphism in the overlying sediments, creating the Marble Unit. In the Central Depression, located outside the metamorphic aureole, lower temperatures are reached and hydrothermalism prevails (Iriarte, 2004; Iriarte *et al.*, 2011). Extensive fluid circulation yielded to remagnetisations observed in the Lower Triassic rocks of the Cinco Villas Massif (Larrasoaña *et al.*, 2003a). The reconstruction of the width of the unroofed domain between the continental margins is uncertain due to the lack of outcrops, but it has been estimated at 10-15 km.

During the Alpine orogeny, major crustal-scale faults were inherited from the hyperextensional period. The Urbasa Thrust and the Leiza-Aralar Thrust System were reactivated from the Cretaceous detachment systems and, together with the decoupling horizon represented by the Upper Triassic evaporites at the base of the basin, accomodated the indentation of the European wedge. The serpentinized body was underthrust to the north and attached to the Iberian crust. As the Leiza-Aralar Thrust System was emplaced, covering most of the Central Depression, the northernmost thrust sheet of the system was eroded. As a result, high-temperature metamorphic rocks of the Marble Unit got in contact with hydrothermal Cretaceous rocks of the Central Depression. New low-temperature thermochronological dating in basement rocks of the Cinco Villas Massif and in basement rocks pinned in the Leiza thrust sheet (DeFelipe *et al.*, 2018b), indicates that the Ollín Fault was reactivated in the late Eocene-Oligocene, slightly later than the Leiza thrust sheet. During the inversion of the Ollín Fault the northern border of the Central Depression was also underthrust. The restoration of the section to the end of the extensional period shows an estimated shortening of ~90 km, which agrees very well with estimations from the most recent plate kinematic model for the Iberian plate since the Late Cretaceous (Macchiavelli *et al.*, 2017).

Discussion

The current crustal architecture of the eastern Basque-Cantabrian Zone is deeply influenced by the pre-orogenic structural configuration. The model proposed in this work for the end of the extensional period (Fig. 4b) is in agreement with recent models proposed for the North-Pyrenean Zone (*e.g.*, Lagabrielle *et al.*, 2010; Clerc *et al.*, 2016; Teixell *et al.*, 2016) and for other areas of the Basque-Cantabrian Zone (Quintana *et al.*, 2015).

Lagabrielle *et al.* (2010) proposed a reconstruction of the Pyrenean structure going back to the Albian in which the mantle was exhumed in the deepest part of the central basins. In their model, a low-angle detachment fault provoked tectonic denudation of the Upper Triassic-Jurassic sedimentary cover which glided towards the bottom of the actively opening basin. The damage zone of the major detachment fault was formed by an assemblage of tectonic slices of crustal and mantle rocks where fluid circulation caused important metasomatic reactions (Corre *et al.*, 2018). Specifically, for their central-eastern Pyrenees section, a north-dipping detachment caused mantle unroofing in the Aulus Basin. Towards the north of their reconstruction, tectonic denudation takes place in the Upper Triassic evaporites and along listric faults in a complex configuration of tilted blocks. Towards the south, the tectonic denudation level cut the middle crust and connected with the subcontinental mantle. This fault is responsible for the formation of the deep Organya Basin in a position slightly away from the rift axis, a configuration that is comparable to that of the Monjardín Fault creating the Cretaceous Urbasa Basin (Fig. 4b).

In the central part of the Basque-Cantabrian Zone, Cretaceous hyperextension yielded also to a very thin crust with the mantle only locally in contact with the upper crust and the Mesozoic sediments (Quintana *et al.*, 2015). The difference with the model presented here is that in the central Basque-Cantabrian Zone the shallowest part in the footwall of the main extensional detachment is occupied by a large piece of the disrupted lower crust instead of the upper mantle. This piece of the lower crust, interpreted to be intesively intruded by gabbros, was later uplifted during the Cenozoic orogenic stage, originating large gravimetric and aeromagnetic anomalies (Pedreira *et al.*, 2007; Quintana *et al.*, 2015).

Our reconstruction for the end of the extensional period (Fig. 4b) is based on a conjugated detachment fault system intially decoupled from a ductile layer in the deep middle crust, as proposed by Sutra *et al.* (2013), following the model of Manatschal (2004). This complex system of detachment faults yielded to a slightly asymmetric basin architecture with mantle rocks underlying the deepest sub-basin of the Leiza detachment system. The Monjardín Fault created a thick Cretaceous basin separated from the elevated Ebro block and connected at depth with the Leiza detachment and the unroofed mantle. The lateral extent of the unroofed domain in Figure 4b is in the range of previous recons-

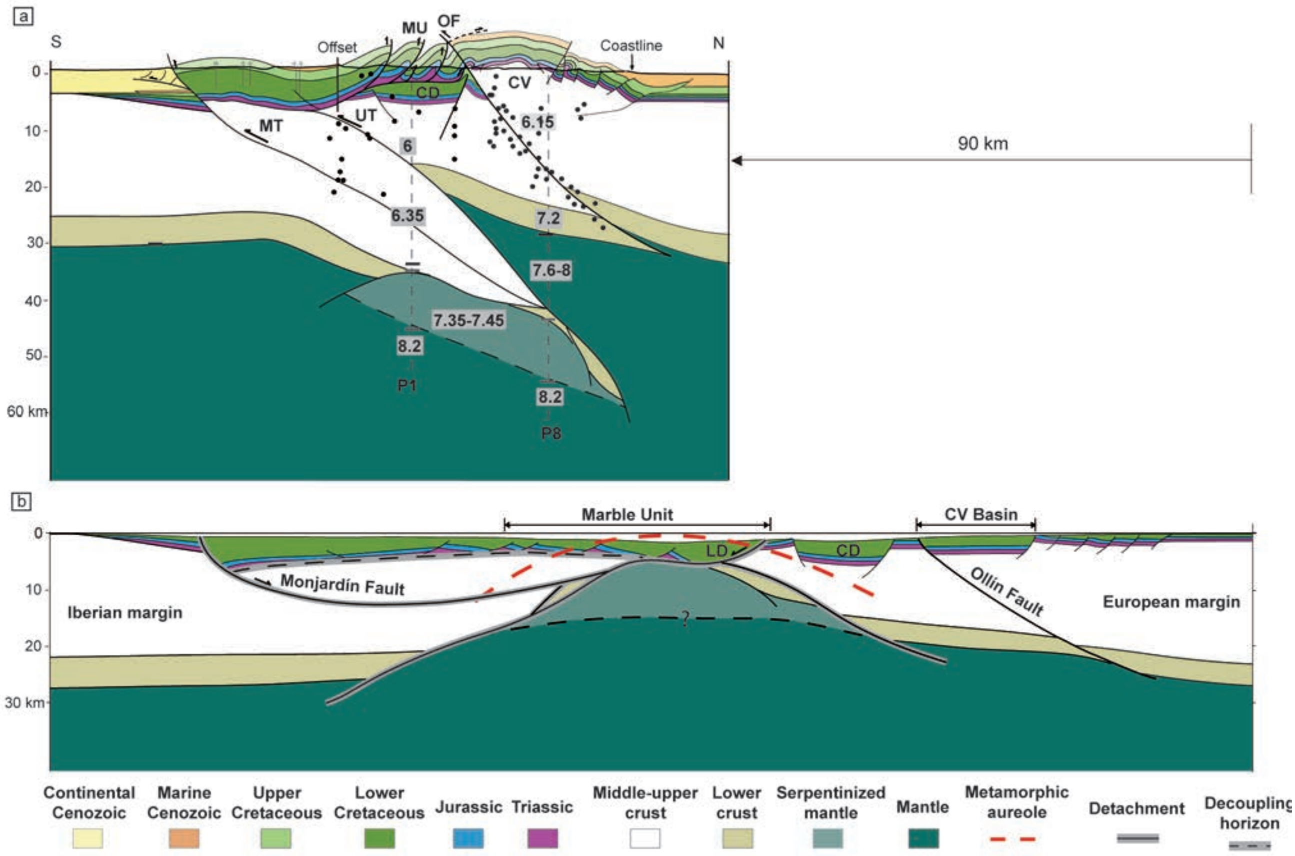

Fig. 4.- a. Crustal-scale transect for the section in Fig. 3. The black dots show superimposed earthquake hypocenters (Ruiz *et al.*, 2006a, b). The black lines are Moho depths according to Díaz *et al.* (2012) and Chevrot *et al.* (2015). The dotted grey lines are the geophysical profiles P1 and P8 by Pedreira *et al.* (2003) and Pedreira (2005) and numbers in grey boxes indicate representative P-wave velocities. b. Restoration of the transect shown in (a.) to the end of the extensional period. Probable extension of the metamorphic aureole is indicated by the dotted red line. OF: Ollín Fault, UT: Urbasa Thrust, MT: Monjardín Thrust, MU: Marble Unit, CV: Cinco Villas Massif, CD: Central Depression, CV basin: Cinco Villas basin, LD: Leiza detachment system.

tructions for the Basque-Cantabrian Basin and the western Pyrenees. Teixell *et al.* (2016) estimated an exhumed domain of *ca.* 15 km for the western Pyrenees and Roca *et al.* (2011) proposed an exhumed domain of 10-15 km for the Basque-Cantabrian Basin. A wider unroofed domain in the eastern Basque-Cantabrian Basin cannot be ruled out, but it would have yielded to mantle exhumation to the sea floor (or eventually, to the formation of oceanic crust), for which there is no evidence in this zone (DeFelipe *et al.*, 2017). Significantly larger convergence would also disagree with shortening estimates provided by recent plate kinematic models (*e.g.*, Macchiavelli *et al.*, 2017).

The Iberian-European plate boundary during the extensional period has been interpreted by Larrasoaña *et al.* (2003a) as an intermediate domain of deformation with pull-apart basins, where the Ollín Fault and the Leiza thrust sheet delimited a transtensional basin during most of the mid-Cretaceous (Iriarte, 2004). However, in our model, restoration leads to thinned crusts in narrow continental margins separated by a domain of unroofed mantle and overlain by a detached sedimentary basin. Thus, the Iberian-Eurasian plate boundary is envisaged as a hyperthinned domain with local mantle unroofing that resulted from hyperextension taking place in the mid-Cretaceous (Jammes *et al.*, 2009; Masini *et al.*, 2014; Tugend *et al.*, 2014). Significant transcurrent movements between Iberia and Eurasia have been recently proposed to occur at an earlier stage, from the Late Jurassic to the Early Cretaceous (*e.g.*, Jammes *et al.*, 2009; Nirrengarten *et al.*, 2018). These left-lateral transcurrent movements could also explain the post-Triassic and pre-Turonian rotations identified by Larrasoaña *et al.* (2003a) arround the Basque Massifs. Also, minor transcurrent movements probably remain during the mid-Cretaceous hyperextension episode, leading to local block rotations (*e.g.*, Agirrezabala and Dinarès-Turell, 2013).

During the Alpine tectonic inversion, the unroofed domain was closed by wedge indentation of the European crust into the Iberian crust. The overlying sediments were detached and thrust onto both continental margins. In our transect, the Urbasa Thrust (Fig. 4) was formed along the previous north-dipping extensional detachment and the Leiza detachment system was reactivated as the Leiza-Aralar Thrust System. This indentation gave rise to the exhumation of the thick Cretaceous basin in the hanging wall of the Leiza-Aralar Thrust System, with complete erosion of the northermost thrust sheets. The emplacement of the Leiza-Aralar Thrust System put together two paleogeographic regions that reached very different temperatures during peak-metamorphism. The Central Depression shows evidence of hydrothermalism at maximum temperatures of 185 ºC (Iriarte *et al.*, 2011) contrasting with the maximum temperatures of 500-550 ºC registered in the Marble Unit (Martínez-Torres, 2008; Ducoux *et al.*, 2018). As no evidence of metamorphism has been described in the Mesozoic materials of the Central Depression, this basin should have been located further away from the mantle body than the Marble Unit. We asume the presence of a horst between the Marble Unit and the Central Depression in the Cretaceous configuration. Describing the stratigraphic units of the Lower Cretaceous in the Leiza-Aralar Thrust Sheet and northern basin, Rat (1988) proposed the presence of a paleo-high separating the "Aralar depression" from the Tolosa area. The resedimented fragments of marbles in the Turonian breccias of the Central Depression (Elgorriaga Formation; Iriarte, 2004) also suggest the existence of a paleo-high located between the Central Depression and the Marble Unit. Towards the north, the Leiza-Aralar Thrust System was underthrust by the Ollín Fault, where thermochronological ages in the Carboniferous rocks of the Cinco Villas Massif are generally younger than in rocks pinned along the Leiza thrust sheet (DeFelipe *et al.*, 2018b).

The *ca*. 90 km shortening estimated for this transect is in agreement with the shortening values estimated for the whole Pyrenean-Cantabrian mountain chain. For the western Pyrenees, Teixell (1998) proposed a shortening of ~80 km, recently enlarged to 114 km (Teixell *et al.*, 2016, 2018) based on the restoration of the upper crustal sedimentary cover, the closure of the exhumed mantle domain and the extensional denudation of the Mesozoic rocks in the continental margins. Jammes *et al.* (2014), however, proposed a minimum shortening of 170 km for the same area, implying a wider Mauléon Basin and a larger domain of exhumed mantle below. For the central Basque-Cantabrian Zone, Pedreira (2005) estimated a shortening of 86 km and Quintana *et al.* (2015) estimated a shortening of 97 km in the upper crust and 122 km in the middle-lower crust. Unbalanced values of shortening of the upper and middle-lower crust may be interpreted as evidence of a mid-crustal flat detachment transferring the orogenic shortening to the Spanish Central System, where a nearly flat Moho seems to be incompatible with the shortening observed at upper crustal levels (Quintana *et al.*, 2015). Conversely, Pedrera *et al.* (2017) estimated a shortening of only 34 km in the central Basque-Cantabrian Zone, contrasting with all previous reconstructions. We have major concerns about the model proposed by these authors (see Pedreira *et al.*, 2018), and therefore consider that their shortening estimate is not reliable.

Regarding to the 3D architecture of the central part of the Pyrenean-Cantabrian mountain chain, the area studied is limited by the Pamplona and Hendaya Transfer Zones. The E-W Pyrenean band of seismicity of the North-Pyrenean Zone continues westward through the Cinco Villas Massif ending abruptly at the Hendaya Transfer Zone (Ruiz *et al.*, 2006b). In addition, the Hendaya Transfer Zone, also marks the eastern termination of the Basque Country Magnetic Anomaly and the Pamplona Transfer Zone seems to align with the western limit of the Labourd-Mauléon Anomaly (Pedreira *et al.*, 2007). All these evidence underscore along-strike structural differences in the central part of the Pyrenean-Cantabrian mountain chain that seems to be controlled by NNE-SSW transfer zones, bounding different segments of the Pyrenean rift inherieted in the Alpine inversion stage.

Conclusions

The general structure of the easternmost Basque-Cantabrian Zone and its reconstruction for the Cretaceous hyperextensional period have been analysed on the basis of a new crustal-scale transect based on structural and geophysical data. This cross-section makes it possible to identify the main geological structure of this area. South of the submerged north-vergent Frontal Thrust, the south-vergent thick-skinned Ollín Fault uplifts the paleozoic Cinco Villas Massif on top of the Central Depression. The southern limit of the Central Depression corresponds to the Leiza-Aralar Thrust System, formed by five north-vergent, thin-skinned thrust sheets detached from the Upper Triassic evaporites. The northern part of the Leiza-Aralar Thrust System, the Marble Unit, experienced Cretaceous high temperature metamorphism. Towards the south, a progressively thicker Cretaceous basin extends until the South-Pyrenean Frontal Thrust, which in this part of the mountain chain is known as the Monjardín Thrust. This corresponds to the southern frontal thrust of the belt which uplifts the Basque-Cantabrian Zone over the Ebro Foreland Basin.

At a crustal scale, the most prominent feature is the indentation of the European crust into the Iberian crust and the northwards subduction of the Iberian crust. This resulted in a basement-cover decoupling in the Iberian crust along the Upper Triassic evaporites and the inversion of the main north-dipping extensional detachment. Three main crustal-scale faults partitioned the structure in this transect: 1) the Ollín Fault, which generates earthquakes that reach depths down to 30 km; 2) the Urbasa Thrust, which may be considered as the present-day limit between the Iberian and European crusts; and 3) the Monjardín Thrust, that runs through the Iberian crust to the surface forming the South-Pyrenean Frontal Thrust. With the available P-wave velocity models, an area of anomalous values (~7.4 km/s) in the deepest part of the Iberian crust beneath a layer with typical middle-crust P-wave velocities could be identified. P-wave velocities of 7.4 km/s are intermediate between those of mantle rocks and lower crustal rocks and have been interpreted here as mantle rocks serpentinized during the extensional period.

The restoration of this transect to the end of the extensional period shows a progressively thinned crust and mantle unroofing to the base of the eastern Basque-Cantabrian Basin. This crustal architecture is enhanced by a complex system of detachment faults with opposite vergences that connect the mantle rocks in the footwalls with the Mesozoic sediments. Once the mantle had been unroofed, extensive fluid circulation caused the serpentinization of the upper part. The thermal anomaly caused high temperature metamorphism in the overlying sediments, forming the Marble Unit. In areas located further from the metamorphic aureole, fluid circulation yielded to hydrothermal processes as described in the case of the Central Depression. A comparison of the present-day and restored sections provides an estimated shortening of *ca.* 90 km, which includes the underthrusting of the serpentinized peridotites.

This study provides new insights into the Alpine structure of the Pyrenean-Cantabrian mountain belt, helping to understand better the 3D architecture of this system. Furthermore, our results shed new light on the processes taking place during the Cretaceous hyperextensional stage in the Basque-Cantabrian Basin, and the role played by inherited structures during the Cenozoic tectonic inversion.

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