12 Alpine Orogeny: Intraplate Deformation

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Abstract

The interior of the Iberian Peninsula contains two types of Variscan crust: (i) unaffected or slightly affected by the Mesozoic extensional events related to the breakup of Pangea, and (ii) stretched during the Mesozoic and eventually thickened during the Alpine orogenesis. The Iberian Massif, the largest outcrop of the European Variscides, as well as the Ebro Block, now hidden under the thick Tertiary cover of the Ebro basin, both belong to the first type of Variscan crust. The second type is identified in the Iberian Chain and the Catalan Coastal Ranges. A review of the various Alpine phases of deformation and the main structures formed in response to them in the two crustal domains is presented in this chapter, as well as a discussion on their timing, the tectonic model and their evolution to the Neogene extensional event that affected Eastern Iberia and during which the opening of the Gulf of Lions and the Valencia Trough occurred.

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12.1 The Iberian Massif

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The interior of the Iberian Peninsula contains two types of Variscan crust:

- Unaffected or slightly affected by the Mesozoic extensional events due to the breaking up of Pangea.
- Stretched and eventually thickened during the Alpine cycle.

The Iberian (also known as Hesperic) Massif, the largest outcrop of the European Variscides, as well as the Ebro Block, now hidden under a thick Tertiary cover of the Ebro basin, both belong to the first type of Variscan crust. The second type is identified in the Iberian Chain or Ranges, to which the Catalan Coastal Ranges can be added, being dealt with in Sect. 12.2.

Although the term Iberian Massif is often used exclusively for the Variscan basement exposures, it should also be realized that part of the Massif is covered either by Tertiary deposits or by a slightly deformed, basement-attached Mesozoic cover. In this sense it represents the non-stretched Variscan crust in the western Iberian Peninsula, whose main morphotectonic characteristics are extensive uplands including Tertiary basins and basement uplifts (likewise the Moroccan and Oranese Mesetas). In this context, the Iberian Massif is also usually referred to as Iberian Meseta, or simply Meseta, enhancing its morphotectonic differentiation in contrast to the surrounding mountainous areas.

The individualization of the Massif occurred in the Latest Triassic-Early Jurassic as a consequence of Pangea's break-up and the subsequent compartmentalization of the Variscan orogen. It represents a piece of non-extended Variscan lithosphere encircled by orthogonal and oblique rifts as well as by an intracontinental transform zone in which stepped extensional basins were developed (Fig. 12.1).

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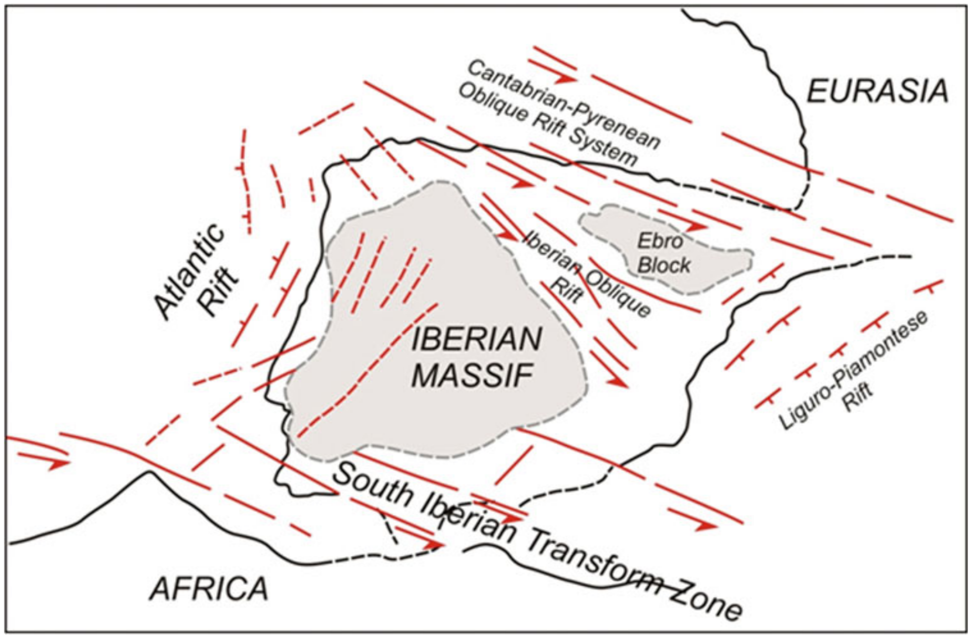

Fig. 12.1 The individualization of the Iberian Massif in the wake of the break-up of Pangaea (after Vegas et al. 2016)

12.1.1 Alpine Phases of Deformation

Alpine tectonics of the Iberian Massif can be divided in two different stages corresponding first to a phase of Mesozoic tectonic quiescence and then to a Cenozoic phase of relative intense deformation.

The *first stage* is a protracted time span of tectonic quiescence and erosion, since Triassic to Latest Cretaceous times, during which the Variscan mountainous topography was erased giving place to an emergent, peneplaned continental fragment. This initial tectonic stage coincides with an extension in the orthogonal rifts, transtension in the transform zone mentioned before (Vegas et al. 2016) and transtension, then extension, in the complex array of oblique rifts (Tugend et al. 2015).

The *second stage* corresponds to a generalized contractive behaviour in the interior of the Iberian plate as a result of the approximation of the African and Eurasian plates. This well documented plate convergence (Dewey et al. 1989; Mazzoli and Helman 1994) was N-S directed from Late Cretaceous to the end of the Oligocene and changed to NW-SE in the Late Miocene, after an imprecise interlude of very low convergence. This allows distinguishing two periods of intraplate tectonics that can be approximately regarded as the *Paleogene* (Pyrenean) and *Neogene* (Betic) phases of deformation in the Iberian Massif.

During the Paleogene phase, the transmission of N-S tectonic stresses from the Cantabrian-Pyrenean edge (the main Africa-Eurasia plate boundary) caused crustal shortening that was later accommodated in an alternation of roughly E-W basement uplifts and basins (probably related to lithospheric folding, Cloetingh et al. 2002) as well as in a NNE-SSW oblique strike-slip fault corridor at the western border of the Massif. It is likely that the main Alpine tectonic features were created in the Iberian Massif during this Paleogene phase (De Vicente and Vegas 2009). In contrast, during the Neogene phase, which was much less intense, far field stresses were transmitted from the newly created main plate boundary, south from the Iberian Peninsula. The subsequent intraplate deformation corresponds to the reactivation of crustal scale structures that were favourably oriented: E-W thick-skin thrusts (Fig. 12.2), NNE-SSW left lateral strike-slip corridors and NW-SE right lateral faults. From this point of view, the NW-SE Iberian Chain domains can be considered as major strike-slip inverted corridors connected to E-W large thrusts.

During this compressive stage of the Alpine tectonic evolution, the crustal shortening was accommodated vertically by the development of mountain ranges (thick-skin tectonics with no inversion) and sedimentary basins which can be related to three crustal folds, a transpressive strike-slip corridor and its contractive terminations (horsetail splay structures). The resulting morphostructural framework for the Alpine deformation is represented in Fig. 12.3, which shows a coherent scheme for the intraplate tectonics in the Iberian Massif.

12.1.2 Main Tectonic Structures

The first order tectonic features correspond to the Central System, a continuous and prominent mountain chain, and to the Northern and Southern Mesetas, two broad, relatively high plateaux containing different ranges and basins.

Fig. 12.2 Example of well-exposed thrust in the northern border of the Central System, central sector (Variscan granite over Cenozoic sediments)

12.1.2.1 The Central System

This outstanding intraplate chain can be defined as a roughly ENE–WSW directed succession of ranges (up to 2500 m high) which extends for more than 700 km, from the Atlantic border to the Iberian Chain, forming the main divide in the Iberian Massif. It emerges above two high plateaux which constitute the Northern and Southern mesetas. The contact with these plateauis always a major thick skin thrust fault (Variscan basement over Cenozoic sediments, Fig. 12.2), currently defined as the Northern and Southern Border Faults, which clearly indicate the compressive origin of this range. The southern thrust seems to accumulate a longer displacement whereas in the north the tectonic structure appears as a series of imbricate thrusts with less individual displacements. This intraplate chain is arranged in fault-bounded individual ranges, which accommodate an important part of the crustal shortening. The orientation of these individual ranges led to a division of the chain in three sectors, whose disposition and main structures are depicted in the Fig. 12.3.

The *western sector* corresponds to two NE directed basement uplifts of the Estrela-Gardunha (1900 m) and the Gata-Sierra de Francia (1700 m) ranges, which are separated by an intermediate low-relief swell that gives continuity to the Central System. The southern border of this intermediate zone corresponds to an E-W fault scarp that continues to the east in the adjacent sector. As a characteristic trait of this sector, the compressive deformation appears to be mainly concentrated in its NE and W borders, along two thrusts corresponding to the Lousã Fault and the northward prolongation of the Ponsul Fault.

The *central sector* presents a roughly E-W (N80) direction, distinctive from the other sectors. It is composed of three longitudinal pop-up like basement elevations, from S to N, the Gredos (2500 m), Paramera (2100 m) ranges and the Ávila platform (1100 m). A ramp basin (thrust-bounded) filled by Tertiary sediments, the Amblés basin, occurs between the Béjar-Ávila and Paramera uplifts, whilst the Gredos and Paramera ranges are separated by a narrow depression. The basin and the depression seem to be in continuation of the north and south borders of the Gata-Sierra de Francia uplifts respectively. The western border of this sector corresponds to two NE-SW alignments of elongated ranges, Béjar (2400 m)- Ávila (1700 m) and Piedrahita (2000 m). They are separated by a narrow depression which corresponds to the northernmost segment of the Plasencia (Messejana-Plasencia) left lateral strike-slip fault. Between this border and the Sierra de Gata-Peña de Francia ranges, an E-W, fault bounded swell gives continuity to the Central System. The eastern border of this sector corresponds to a NE-SW alignment of small ranges, including the Malagón and West Guadarrama ranges, related to a complex, reactivated fault zone, which we name here as El Escorial fault system. In summary, the overall arrangement of basement uplifts and depressions indicates that the compressive deformation was mainly taken up by nearly E-W thrusts in this sector whereas the compressive stresses were nucleated along the NE-SW inherited faults.

The *eastern sector* extends between the small and elongated ranges of the El Escorial fault zone and the NW-SE directed Somolinos right lateral strike-slip fault, which is considered the western limit of the Iberian Chain. From N to

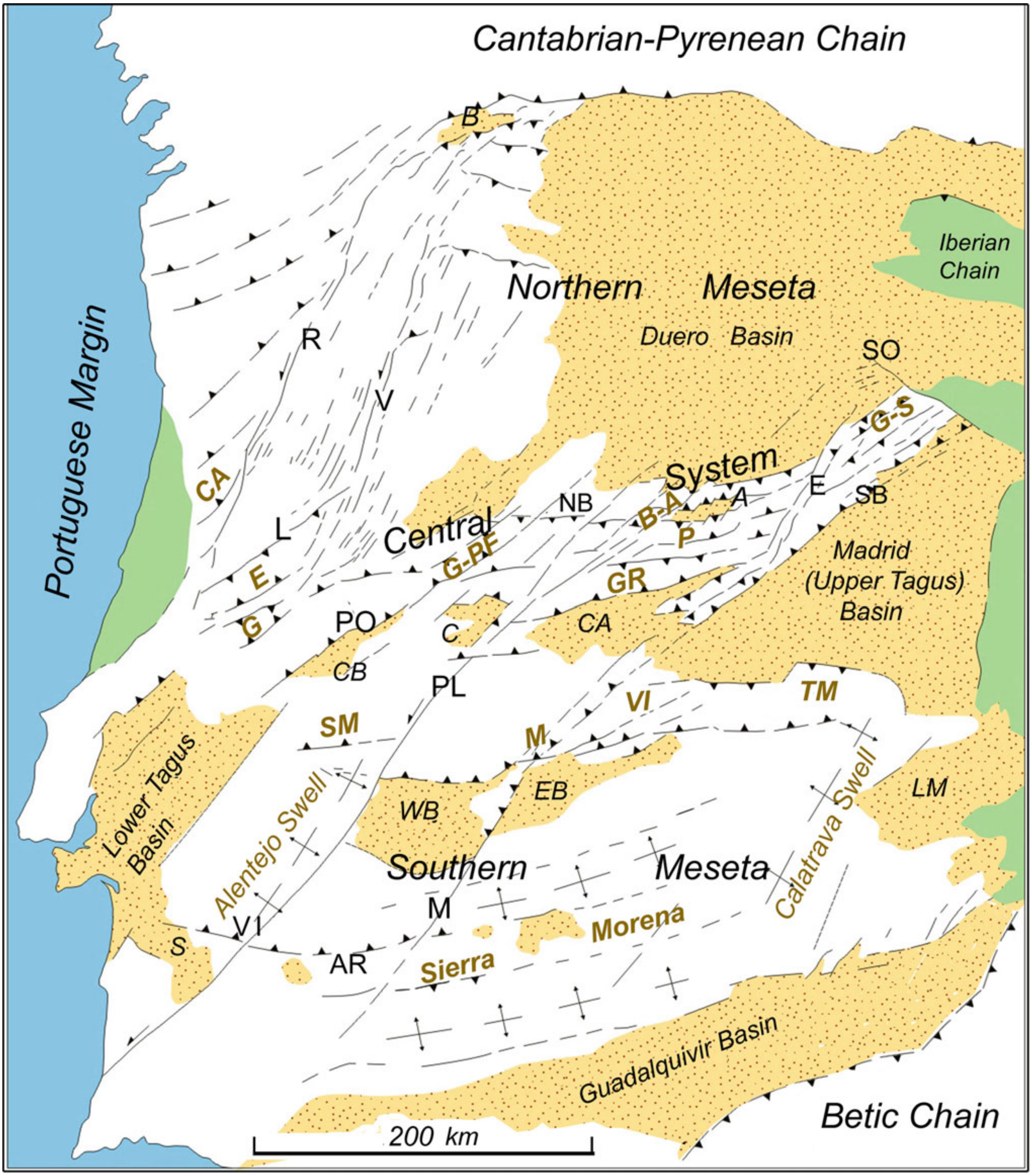

Fig. 12.3 Main Alpine tectonic features in the Iberian Massif. Faults (barbed lines for thrusts): AR: Ardila, E: El Escorial, L: Lousã, NB: Northern Border, M: Mérida, PL: Plasencia (Messejana Plasencia), PO: Ponsul, R: Regua, SB: Southern Border, SO: Somolinos,V: Vilariça, VI: Vidigueira. Basement uplifts: B-A: Béjar-Ávila, C: Caramulo, E: Estrela, EB: Eastern Badajoz, G: Gardunha, GR: Gredos, G-R: Guadarrama-Somosierra, P: Paramera, SM: São Mamede, TM: Toledo Mountains. Cenozoic basins (dotted yellow): A: Amblés, B: Bierzo, C: Coria, CA: Campo Arañuelo, CB: Castelo Branco, LM: La Mancha, S: Sado, WB: Western Badajoz

S, this sector consists of two NE-SW alignments of ranges, East Guadarrama-Somosierra (2400 m) and Morcuera, and a large platform containing two stepped thrusts related to internal minor sierras and depressions. The two main uplifts are separated by a complex depression which in its western part contains a NNE-SSW ramp basin filled by Cretaceous marine sediments. The southern border of this sector is a clear thrust fault, the so-called Southern Border Thrust, that extends southward in the southern Meseta as part of a long fault zone. In turn, the northern border corresponds to a series of imbricate thrusts which affect the basement and its Mesozoic cover (De Vicente et al. 2009).

12.1.2.2 The Northern Meseta

This area corresponds to the Variscan crust situated between the Cantabrian orogenic front and the northern border of the Central System. Most part of it forms an elevated plateau (900–800 m) that contains the almost enclosed Duero Basin, filled by Tertiary sediments. In its western border, the plateau is crossed by a NNE-SSW wide (ca. 100 km long), confined strike-slip corridor with a positive flower structure formed by two main left-lateral faults, Regua and Vilariça, and the intermediate *planalto* between them. The mechanisms of deformation in the Northern Meseta have been ascribed to crustal flexure and accumulation of sediments in the plateau, and to the transmission of crustal shortening from the orogenic front to the eastern segment of the Central System along the transcurrent faults of the deformation belt (Vegas et al. 2004).

The *plateau* is almost entirely covered by the Tertiary sediments of the Duero basin; the basement is only exposed north of the eastern sector of the Central System, in the prolongation of the Sierra de Gata-Peña de Francia, and also along the border of the corridor characterized by the pervasive NNE-SSW fabrics. The Duero basin represents a good example of an intraplate basin generated in a constrictive regime. To the north it is limited by the orogenic front of the Cantabrian-Pyrenean Mountains, and acts as a foreland basin, whereas in the south it is limited by the complex arrangement of thrusts forming the northern border of the Central System.

The *NNE-SSW strike-slip corridor* comprises two main left-lateral faults or fault zones, Regua and Vilariça, delineated by the alignment of elongate small ranges and subsidiary basins, typical of compressive strike-slip corridors with good examples of small push-up ranges and pull-apart Cenozoic basins. These faults are situated within and close to the borders of a shear band delimitating the corridor; their compressive terminations must be in some way connected to the border thrusts of the Cantabrian Mountains to the north and to the eastern border of the Estrela and Gardunha ranges (Fig. 12.3). Moreover, other ranges and related thrusts can be ascribed to the northern compressive horse-tail type terminations. This is the case of the NW-SW Sanabria and Cabrera basement uplifts (2100 m), which emerge over the plateau and also over El Bierzo Tertiary basin. In the same sense, the NE-SW ranges of Pradela, Marão (1400 m) and Caramulo can be ascribed to compressive thrusts related to the highly distributed shear related to the Regua fault.

12.1.2.3 The Southern Meseta

The southern part of the Iberian Massif, between the Central System and the Guadalquivir Basin (Fig. 12.3), corresponds basically to a large peneplain (400 m high) tilted and highly incised to the west. In contrast to its northern counterpart, it is opened to the Atlantic margin and is structured in an alternation of ENE-directed alignments of basins and basement uplifts.

The northern alignment of fault bounded basins mimics the overall arrangement of the uplifted segments in the Central System. Accordingly to this, it can be divided in three sectors separated by the two long, NE-SW fracture lines that cross the Southern Meseta. In this context, the western sector contains the basins of Castelo Branco and Coria and is framed by the NE-SW Ponsul and Plasencia faults. The central sector is occupied by the Campo Arañuelo and Tiétar Tertiary basins which are laterally bordered by two NW-SW swells related to the Plasencia fault line and also to the prolongation of the southern border of the Central System. The eastern sector corresponds to the triangle-shaped Upper Madrid basin which is encircled by the Central System, the western front of the Iberian Chain and the Montes de Toledo uplift and its prolongation in a shallow swell, known as the Alcázar Swell.

An almost continuous alignment of fault-bounded basement elevations develops to the south of these basins. The ranges can be grouped in three sectors separated by the same NE-SW long fault lines as in the case of the basins. The western sector corresponds to the Serra de São Mamede (1000 m) and to the northern continuation of the Sierra de San Pedro, which form part of an uplifted block limited by E-W thrusts. The central sector is occupied by the Cáceres platform, a ramp developed in the rear of the prominent NE-SW thrust which bounds the Sierras de Montánchez (1000 m). It must be stressed that this thrust is a segment of the NE-SW fracture line which forms the southern border of the Guadarrama-Somosierra basement uplift and extends to the south through the rest of the Southern Meseta. The eastern sector is represented by the broad basement uplift of Guadalupe-Villuercas (1600 m)-Montes de Toledo (1300 m), which is situated to the east of the NW long fracture line mentioned before. This basement elevation is bounded to the north by the E-W Toledo Thrust and to the south by the Guadalupe Thrust and its continuation in the Montes de Toledo.

The other alignment of tectonic depressions contains the Guadiana (or Badajoz) and La Mancha basins filled by

Neogene sediments. In fact, the Guadiana Basin corresponds to two sub-basins separated by a narrow NE-SW swell limited by the Mérida Fault, which also pertains to the NW long fracture line mentioned in the previous paragraphs. In fact, this fault line could be named as Mérida-South Border of Guadarrama or simply Mérida Fault (Vegas et al. 2012). The semi-endorheic La Mancha Basin seems to be limited by NE-SW ill-defined faults and is separated from the Guadiana basin by an oblique NNE-SSW basement up-arching, called the Calatrava Swell (Granja-Bruña et al. 2015; Fig. 12.3).

The southernmost Alpine structure in the Southern Meseta is the basement uplift of Sierra Morena. It is an almost continuous and asymmetric, overlying up-arching with heights up to 1000 m decreasing clearly to the W. This E-W up-arching contains two longitudinal stripes of overlying reliefs which are separated by a central low-relief zone. This intermediate low-relief zone contains several small Tertiary basins, and is bounded by the Ardila Fault to the north and the Aroche Fault to the south at its western termination. Furthermore, these are the only evident Alpine faults in the interior of the Sierra Morena and the Ardila fault seems to continue in the well exposed reverse fault of Vidigueira in southern Portugal (Cabral and Ribeiro 1988; Cabral 1995). With regard to the borders of the Sierra Morena uplift, no evidences of clear reverse faults have been described, with the exception of the alignment of some reliefs in the form of morphotectonic lineaments. In this sense it is tentatively possible to envisage the existence of blind thrusts at the borders of the two parallel high-relief zones forming the Sierra Morena.

To the west, the Alpine tectonic features also include the NNE-SSW Tertiary basin of the lower Tagus and an adjacent and parallel basement swell, named here as Alentejo Swell, which hampered the Atlantic drainage of the Guadiana (Fig. 12.3).

In summary, crustal shortening in the Southern Meseta was accommodated first by means of basement uplifts and related basins and subsequently by the reactivation of faults as well as by superimposed crustal swells.

12.1.3 Tectonic Model

Until recent times, no comprehensive tectonic model had been proposed for the large-scale distributed deformation of the lithosphere in the interior of the Iberian Peninsula. The existence of far-field compressive stresses from the Cantabrian-Pyrenean orogenic front led to assume the differential uplift of many areas of the Iberian Massif (De Vicente and Vegas 2009). As shown before, the internal deformation in the Massif is nucleated between a confined strike-slip deformation belt and several basement uplifts. This strike-slip belt accommodates the horizontal crustal shortening in its compressive terminations whereas the basement thrusts accommodate the crustal shortening by buckling. The latter have been ascribed to a process of lithospheric folding (Cloetingh et al. 2002). This is consistent with results of a spectral analysis of gravity and topography of central-western Iberian Peninsula (Muñoz-Martín et al. 2010) that confirms the existence of dominant 200 (± 50) km wavelength undulations on both the topography and the gravity field. The gravity power spectra also shows a larger wavelength of at least 500 km, which probably reflects the high average elevated base level of the Iberian Peninsula, with a steep contrast at the borders. These characteristics of the signal spectra have been interpreted in terms of lithospheric folding in response to Alpine (Pyrenean) tectonics. The presence of different wavelengths in the gravity and topographic signals could be related to mechanical decoupling of the Iberian lithosphere.

12.2 The Iberian Chain and the Catalan Coastal Ranges

De Vicente G, Casas-Sainz A, Vegas R

During the Early Mesozoic, an extensional event occurred surrounding the Iberian Variscan crust (Doblas et al. 1994). This event diagonally broke through the Iberian interior forming a set of rift basins (García-Lasanta et al. 2015). They were aligned between the Cantabro-Pyrenean transcurrent rift zone and the extensional structures linked to the western margin of the Jurassic Liguro-Piamontese Ocean (now vanished). These rifts constitute the so-called *Mesozoic Iberian Rift Zone* (MIRZ) and were eventually inverted during the intraplate Cenozoic compressive events, giving rise to the Iberian Chain or Iberian Ranges. At the same time, the extensional structures related to the Liguro-Piamontese margin, situated at a high angle to the Iberian rifts, were also inverted at the Catalan Coastal Ranges. Both the Iberian and Catalan Coastal ranges are summarized here according to its present intraplate location and its post-Mesozoic evolution.

Extension in the MIRZ occurred during two main episodes. The first event (Arche and López-Gómez 1996; see also Chap. 3 in this volume) began in the Early Triassic (Andesitic volcanism is previously registered during Permian times). It coincided in time with the initiation of the Central Atlantic rifting between Africa and North America, and ended during the Early Cretaceous with the opening of the Atlantic Ocean between Iberia and Newfoundland. Anyhow, extension was predominantly oblique (with a left-lateral component). The second extensional event occurred during the Middle-Late Cretaceous time span (Liesa et al. 2006; Rodríguez-López et al. 2007;

García-Lasanta et al. 2016) and ended when Africa-Europe convergence started. In this case, the extension was almost perpendicular to the rifted basins.

In the other hand, an episode of Early Triassic-Jurassic orthogonal extension can be recorded for the previous structures related to the Catalan Coastal Ranges.

From a general point of view, the Iberian Chain has been classically considered as an Aulacogen (Alvaro et al. 1979), a lateral branch of the Ligurian-Betic rift. However, its location close to the Northern and Southern, eventually convergent, Iberian plate margins and its oblique orientation gave place to a more complicated history; both during the extensional Mesozoic period and the Cenozoic inversion stage. A regional, Albian unconformity and an early compressional event at ca. 100 Ma contribute to this more complex scenario.

Intraplate deformation in the Iberian Chain and the Catalonian Ranges involved thin- and thick-skinned tectonics and a basement-cover regional detachment in the Middle-Upper Triassic shales and evaporites, both during extension and compression. However, the existence of a thick Paleozoic cover with low metamorphism (approaching 10 km in thickness) and a lower décollement (Precambrian shales) also imposed some constraints on deformation, especially in areas where the Mesozoic cover was significantly thin, forming long-wavelength thrust-related folds (Casas-Sainz and Faccena 2001; Simón 2004).

12.2.1 The Iberian Chain

The inversion of the different rifts (and related structures and basins) of the MIRZ is the scenario to divide the Iberian Chain into two main deformation belts, the North (≈ Aragonese) and South (≈ Castilian) branches. Both Cenozoic deformation belts correspond to two inverted Triassic grabens, whereas the Almazán Cenozoic Basin and a good part of the North Branch drew a sedimentary high at this stage (Muñoz, 1993; Casas-Sainz et al. 2000; Salas et al. 2001).

The North Branch also includes specific sectors: The Cameros-Demanda zone, the Maestrazgo zone and the Linking Zone (Portalrubio-VandellòsThrust Belt) that makes the transition to the Catalan Coastal Ranges. The South Branch comprises several different zones: The link area with the Central System, the Cuenca Ranges, the Valencian Sector, the Altomira Range and the transition to the Prebetic Zone (Fig. 12.4).

Crustal thickness is up to 40 km at Cameros-Demanda, whereas it is around 37 km below the Linking Zone and in some areas of the North and South branches. The Catalan Coastal Ranges shows a thinner crust with typical values ranging between 27 and 30 km (Diaz and Gallart 2016).

12.2.1.1 The North Branch

The structure of this sector is defined by two NW-SE Paleozoic outcrops separated by the Cenozoic Calatayud basin. Most part of this basin shows thicknesses of a few hundred meters of syn-to post-tectonic deposits, although at its eastern edge 2000 m of Upper Eocene-Miocene sediments are preserved, associated with intramontane basin formation at the front of thrusts responsible for the inversion of the Maestrazgo Basin (Antolín-Tomás et al. 2007). The North Branch underwent a limited subsidence history and only post-rift sequences (Jurassic and Upper Cretaceous) are well represented, although magmatism of mantellic affinity is recorded in the Triassic successions. Uplift during the Cenozoic inversion was controlled by flexural-slip reactivation of Variscan folds, dextral strike-slip faulting along Late-Variscan fractures parallel to the main structural trend, and limited thrusting at the Cenozoic basin borders (Cortés and Casas-Sainz 1996). Transpression and strain partitioning between vertical strike-slip faults and thrusts was common during this stage.

The Cameros-Demanda Sector and the Maestrazgo Basin

The Cameros basin underwent a particularly strong subsidence history during the Late-Jurassic-Early Cretaceous, favoring the accumulation of 8000 m of continental (fluvial, lacustrine and deltaic) syn-rift deposits (Villena et al. 1996; Muñoz-Jiménez and Casas-Sainz 1997, see also Chap. 5 of this volume). The extension direction was mainly NE-directed with episodes (Aptian) switching to NW-SE. Its inversion during the Cenozoic (Late Eocene-Middle Miocene) formed the most prominent thrust structure in the Iberian Chain, having a horizontal displacement of nearly 30 km and a vertical throw of about 4 km. The Upper Triassic (Keuper) detachment level played a major role in the compressional structuring of the thrust that to the West and East involved the Variscan basement (Demanda and Moncayo Sectors; Casas-Sainz and Gil-Imaz 1998; Casas-Sainz et al. 2016). The transport direction for the thrust was approximately N-S, showing its counterpart (Pyrenean thrust system) on the opposite side of the Ebro basin, filled with syn-tectonic deposits (Fig. 12.5a).

The Maestrazgo basin is the other strongly subsiding area in the Iberian Chain. It accumulated more than 2500 m of Lower Cretaceous marine deposits, linked to extension associated with the Tethyan margin and the Iberian realm. Its inversion during the Cenozoic was strongly controlled by previous extensional structures, especially in marginal areas where the sedimentary cover is thinner (Casas et al. 2000; Nebot and Guimerà 2016). Basement thrusting was transferred to the cover through the Middle Triassic detachment (Utrillas and Linking Zone thrusts) (Simón and Liesa 2011) (Fig. 12.5c).

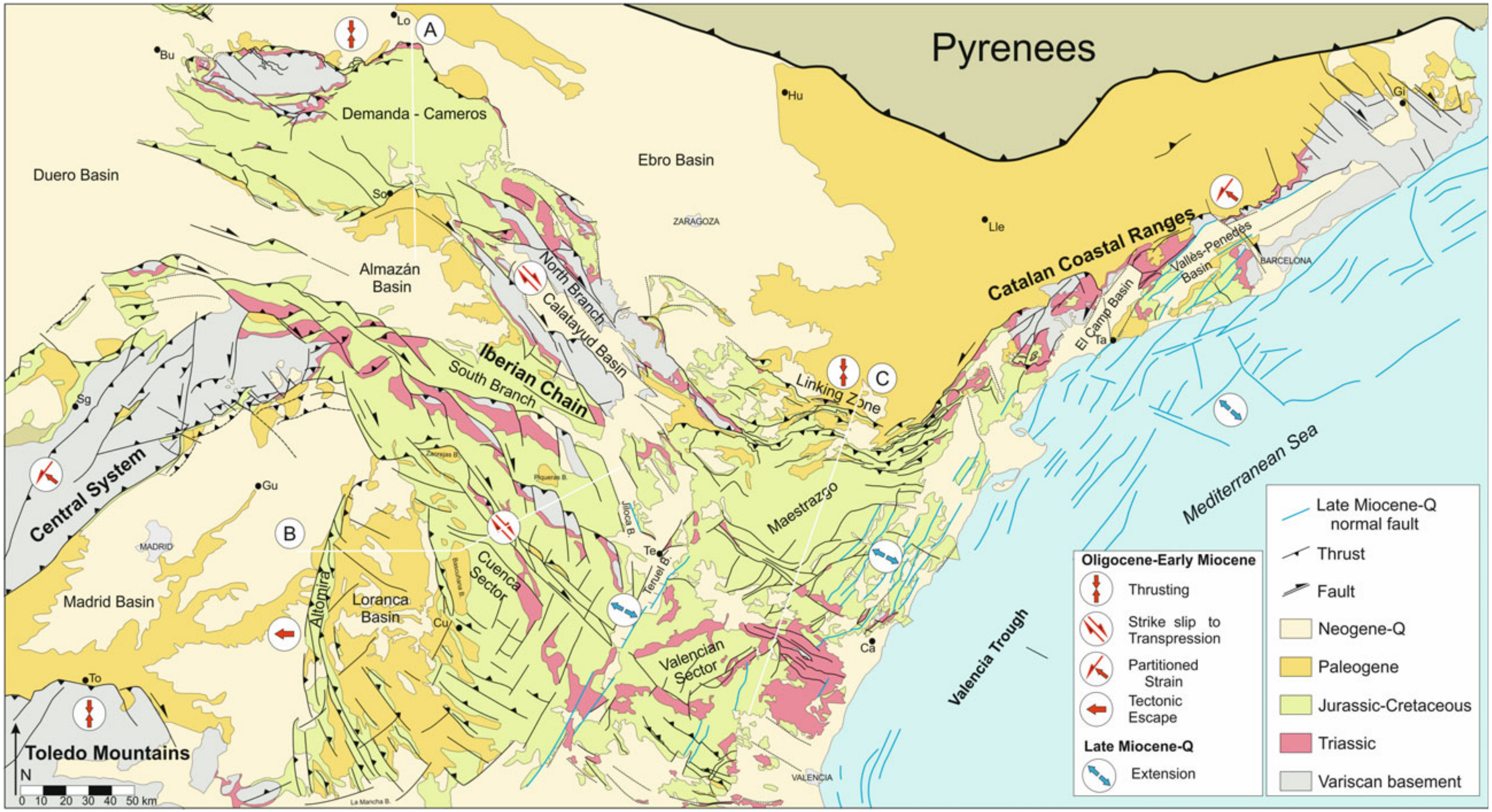

Fig. 12.4 Tectonic map of the Iberian Chain with location of the different sectors considered. Main deformational modes are also shown: Thrusting, Strike-slip to transpression, partitioned strain and thin skin tectonic escape. Late Miocene to Quaternary extension is drawn by blue faults and arrows

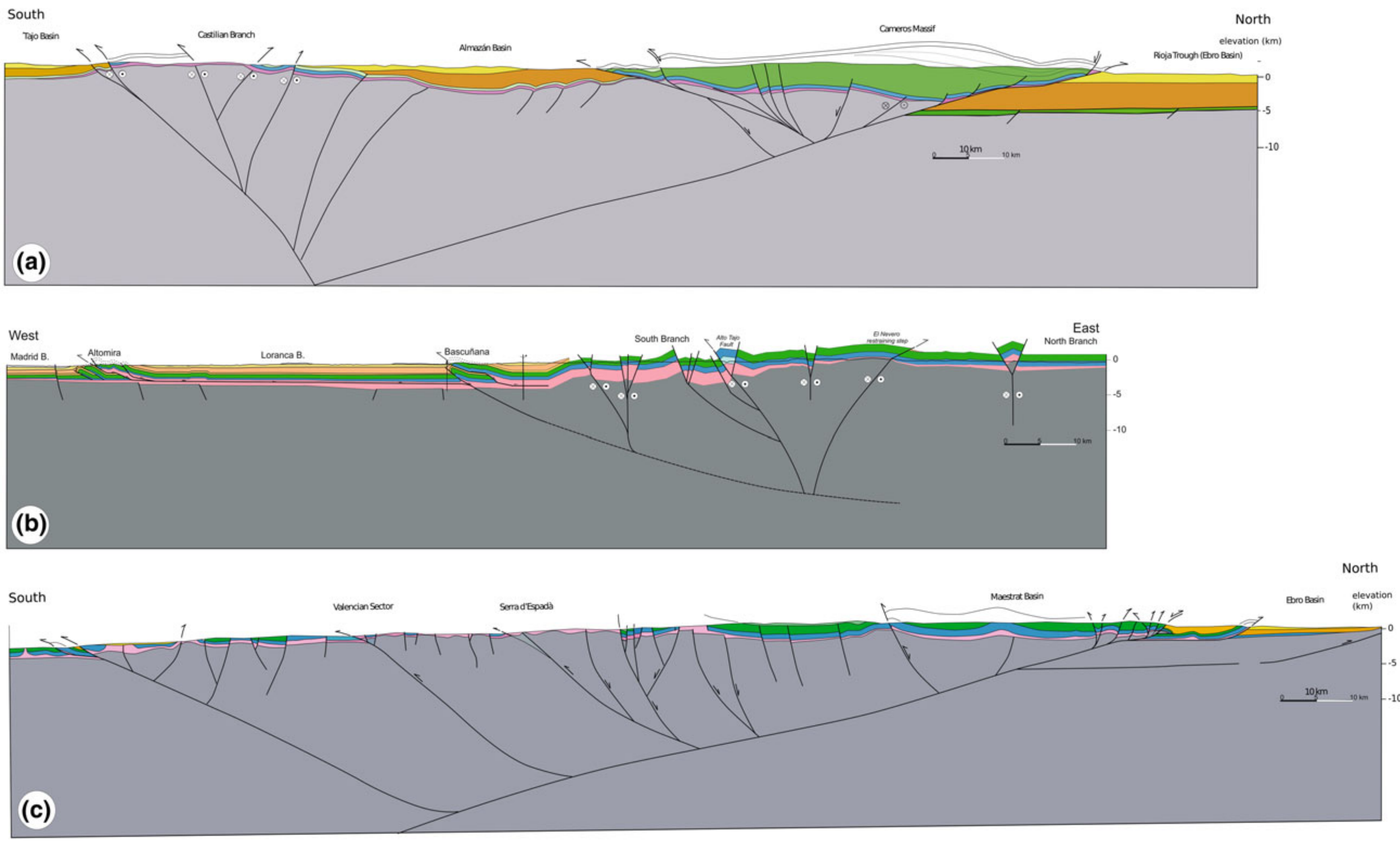

Fig. 12.5 Cross sections (Location in Fig. 12.4): **a** Cameros-Demanda and the northern sector of the South Branch of the Iberian Chain. **b** Central sector of the South Branch and the Altomira Range. **c** Maestrazgo and the Valencian sector. Grey: Variscan basement; pink: Triassic; blue: Jurassic; green: Cretaceous; orange: Paleogene; yellow: Neogene

12.2.1.2 The South Branch

Main previous faults here were NW-SE oriented normal faults related to the first extensional event (Triassic). During the Cretaceous extension, a gentle syncline can be drawn below the siliciclastic sediments of the Utrillas Fm. So, extension during this second episode was not important, but probably some kind of transtensional deformation took place (De Vicente et al. 2009).

During the Cenozoic inversion (Oligocene-Early Miocene) these heterogeneities moved as right lateral strike-slip faults bordering a NW-SE transpressive deformation belt with NE-SW en échelon folds (close to the Central System) (De Vicente el al. 2009). Pure strike-slip and positive flower structures developed in the sedimentary cover southwards, giving rise to straight and long-running NW-SE folds like along the Alto Tajo fault. At the edges of these flowers, local lined NW-SE reverse faults can also occur (e.g. El Portillo) (Barrier et al. 2002) but without the twisted typical geometry of other E-W pure thrusts in the Iberian Chain (e.g. the Cameros thrust). All these structures must merge at depth in a single basement strike-slip fault. Local E-W restraining steps are also evident. Both N and S tectonic transports are observed and basement wedges can outcrop in the hanging wall of the steps. At the same time, local basins appear in the footwalls with progressive unconformities (e.g. Zaorejas and Piqueras basins). All these structures and fold trends have been explained as a result of a single N-S (Pyrenean) compression through a strain partitioning process within a NW-SE transpressive zone (de Vicente et al. 2009) (Fig. 12.5b). The Central System is a crustal intraplate pop-up with a vertical throw of ca. 5 km at the south. Taking this into account, the South Branch of the Iberian Chain represents a large scale tear fault that accommodates sideways this significant shortening.

The Valencian Sector and the Altomira Range

The prolongation towards the S and SE of the South Branch defines the Valencian Sector, where Triassic and Jurassic outcrops dominate, without a clear structural trend. The significant thickness of evaporitic Upper Triassic deposits favored the formation of diapirs and the detachment of the Jurassic cover. Towards the West, the Serranía the Cuenca and the Sierra de Altomira show a structural trend oblique to the tectonic grain of the Iberian Chain, resulting from the westwards thinning of the regional detachment and/or thin skin escape tectonics giving rise to a narrow N-S thrusting belt that widens to the south (Muñoz-Martín 1997; Valcárcel et al. 2016) (Fig. 12.5b).

12.2.2 The Catalan Coastal Ranges and the Linking Zone

The Cenozoic inversion of the Mesozoic rifts defined in the Catalan Coastal Ranges a similar structure (both in direction and style, i.e. strain partitioning) to the Central System. In fact, this range corresponds to a Paleogene uplift of Variscan basement and to its attached cover on which a Neogene extensional event was later superimposed (Vegas et al. 1979).

Thick-skinned thrusts showing kilometric vertical displacements appear all along the northern border of the range, forming the limit with the Ebro basin, where a series of syn-tectonic unconformities are present within the syn-tectonic sediments (Guimerà 1984; Guimerà and Álvaro 1990). In the northern segment of the Catalonian Range, reactivation of Late-Variscan faults played a major role in its final structure, showing in general a left lateral component. Conversely, towards the South, the presence of the Middle-Upper Triassic detachment and a significant overlying sedimentary cover defined a different tectonic style, that continues towards the Linking Zone and the Iberian Chain. In the Linking Zone the two main structural trends (NE-SW, corresponding to the Catalonian Range, and NW-SE, typical of the Iberian Chain) coexist, conforming interference patterns that can be followed for tens of kilometers along the trend. The Linking Zone structures draw an arc-like geometry concave towards the south, while the other area with intense thrusting (Cameros-Demanda) is concave towards the north. Both areas can be explained by N-S shortening.

12.2.3 Age of the Tectonic Inversion of the Mesozoic Rift

The compressional deformation of the Iberian plate is related to the evolution of its Northern (Pyrenean) and Southern (Betic) margins. The timing of deformational events, recorded in the filling of the main terrestrial internally drained basins (Ebro, Duero and Tajo), shows an evolution from North to South. In the Pyrenees, the main foreland basins (first with turbiditic, then with molasse filling) formed between the Middle Eocene and the Early Oligocene. In the Iberian Chain, syn-tectonic deposition associated with thrusting and folding occurred from the Late Eocene until the Early Miocene. Apatite fission track data show an important cooling event in Cameros between 31 and 40 Ma (Del Río 2009), also registered in the Central System (De Bruijne and Andriessen 2002) and in the westernmost part of the Cantabrian Pyrenees (Fillon et al. 2016). Thus, most part of the intraplate deformation in Iberia was related to the Pyrenean foreland. Nevertheless, the Betic orogen was also able to transmit effective compressional stresses towards the Iberia interior during a short period of time. The change from marine facies to continental ones took place in the Betics most external deformation belt (the Alcaraz Arch) during the Tortonian (Hüsing et al. 2012). Because of the fast evolution (decoupling) of the Alborán Domain, extension is registered nowadays in the eastern Betics foreland (De Vicente et al. 2008). So, the Betics-related intraplate deformation took place only during the 8–3 Ma time span. This process reactivated some previous Pyrenean structures, as in the Central System (also registered in AFT data) and in Cameros. Late Miocene-Pliocene alluvial fans are clearly related to this event, but the total volume of sedimentation is much less than the one related with the Oligocene-Early Miocene (Pyrenean) compression.

12.2.4 The Neogene Extension Related to the Opening of the Gulf of Lions and the Valencia Trough

Finally, a Neogene extensional event (Vegas et al. 1979; Simón 1983) related to the opening of the Gulf of Lions and the Valencia Trough changed the depositional environments and topography of the Eastern margin of Iberia, especially the Catalonian Coastal Range and the Maestrazgo sector and, to a limited extent, the Eastern part of the Iberian Chain (Teruel and Jiloca basins) (Simón et al. 2012). In the Catalonian Coastal Ranges extension was responsible for the splitting of the basement uplift into two parallel ranges (Litoral and Prelitoral) separated by a series of Neogene basins, oblique to the coastline (Vallès-Penedès, El Camp and Baix Ebre), in a horst-graben arrangement (Fig. 12.4). Related sediment thickness is more than 3000 m (Bartrina et al. 1992).

In the Maestrazgo area, Neogene basins are parallel to the coastline (Fig. 12.4) but thickness of syn-extensional deposits is much lower than in the Catalonian Range. The horst and graben system is also expressed in the particular morphology of the area. Most normal faults are rooted in the Paleozoic basement and are probably inherited from the Mesozoic rift system with Tethyan polarity. This extensional process continues nowadays. The Concud (the eastern limit of the Teruel Basin) and El Camp normal faults are active structures (Simón et al. 2012; Masana et al. 2001). Nevertheless, NW-SE oriented normal focal mechanisms are also registered, and the state of active stresses is triaxial extension (De Vicente et al. 2008). This could indicate some kind of post-compressional collapse of the eastern ranges of Iberia (Casas-Sainz and De Vicente 2009).

References

Álvaro M, Capote R, Vegas R (1979) Un modelo de evolución geotectónica para la Cadena Celtibérica. Acta Geológica Hispánica 14: 172–177.

Antolín-Tomás B, Liesa CL, Casas AM, Gil-Peña I (2007) Geometry of fracturing linked to extension and basin formation in the Maestrazgo basin (Eastern Iberian Chain, Spain). Revista de la Sociedad Geológica de España 20(3–4): 351-365.

Arche A, López-Gómez J (1996) Origin of the Permian-Triassic Iberian Basin, central-eastern Spain. Tectonophysics 266(1): 443–464.

Barrier L, Nalpas T, Gapais D, Proust JN, Casas A, Bourquin S (2002) Influence of syntectonic sedimentation on thrust geometry. Field examples from the Iberian Chain (Spain) and analogue modelling. Sedimentary Geology 146(1): 91–104.

Bartrina MT, Cabrera L, Jurado MJ, Guimerà J, Roca E (1992) Evolution of the central Catalan margin of the Valencia trough (western Mediterranean). Tectonophysics 203(1–4): 219-247.

Cabral J (1995) Neotectonica em Portugal Continental. Memórias do Instituto Geológico e Mineiro 31, 263 p.

Cabral J, Ribeiro A (1988) Carta Neotectónica de Portugal Continental, Escala 1:1.000.000. Editorial dos Serviços Geológicos de Portugal, Lisboa.

Casas AM, Casas A, Pérez A, Tena S, Barrier L, Gapais D, Nalpas T (2000) Syn-tectonic sedimentation and thrust-and-fold kinematics at the intra-mountain Montalbán Basin (northern Iberian Chain, Spain). Geodinamica Acta 13(1): 1–17.

Casas-Sainz AM, Faccenna C (2001) Tertiary compressional deformation of the Iberian plate. Terra Nova 13(4): 281–288.

Casas-Sainz AM, De Vicente G (2009) On the tectonic origin of Iberian topography. Tectonophysics 474(1): 214–235.

Casas-Sainz AM, Gil-Imaz A (1998) Extensional subsidence, contractional folding and thrust inversion of the eastern Cameros basin, northern Spain. Geologische Rundschau 86(4): 802–818.

Casas-Sainz AM, Cortés-Gracia AL, Maestro-González A (2000) Intraplate deformation and basin formation during the Tertiary within the northern Iberian plate: Origin and evolution of the Almazán Basin. Tectonics 19(2): 258–289.

Casas-Sainz AM, Román-Berdiel T, Oliva-Urcia B, García-Lasanta C, Villalaín JJ, Aldega L, Osácar MC (2016) Multidisciplinary approach to constrain kinematics of fault zones at shallow depths: a case study from the Cameros–Demanda thrust (North Spain). International Journal of Earth Sciences, 106(3):1023–1055.

Cloetingh S, Burov E, Beekman F, Andeweg B, Andriessen PAM, Garcia-Castellanos D, De Vicente G, Vegas R (2002) Lithospheric folding in Iberia. Tectonics 21(5): 1041. https://doi.org/10.1029/2001tc901031 https://doi.org/10.1029/2001tc901031.

Cortés A, Casas Sainz AM (1996) Deformación alpina de zócalo y cobertera en el borde norte de la Cordillera Ibérica (Cubeta de Azuara-Sierra de Herrera). Rev. Soc. Geol. España 9: 1–2.

De Bruijne CH, Andriessen PAM (2002) Far field effects of Alpine plate tectonism in the Iberian microplate recorded by fault-related denudation in the Spanish Central System. Tectonophysics 349: 161–184.

De Vicente G, Vegas R (2009) Large-scale distributed deformation controlled topography along the western Africa–Eurasia limit: Tectonic constraints. Tectonophysics 474(1–2): 124-143.

De Vicente G, Cloetingh S, Muñoz-Martín A, Olaiz A, Vegas R, Galindo-Zaldivar J, Fernández-Lozano J (2008) Inversion of moment tensor focal mechanisms for active stresses around the microcontinent Iberia: Tectonic implications. Tectonics 27: 1–22. https://doi.org/10.1029/2006tc002093.

De Vicente G, Vegas R, Muñoz-Martín A, Van Wees JD, Casas-Sáinz A, Sopeña A, Sánchez-Moya Y, Arche A, López-Gómez J, Olaiz A, Fernández-Lozano J (2009) Oblique strain partitioning and transpression on an inverted rift: The Castilian Branch of the Iberian Chain. Tectonophysics 470: 224–242.

Del Río P (2009) Historia termal del sector oriental de la Sierra de Cameros: restricciones a partir del análisis de huellas de fisión en

apatitos y otras herramientas geocronológicas (U-Pb SHRIMP y (U-Th)/HE). PhD Thesis, Universidad de Zaragoza, 342 p.
Dewey JF, Helman ML, Turco E, Hutton DHW, Knot TSD (1989) Kinematics of the western Mediterranean. In: Coward MP, Dietrich D, Park RG (eds), Alpine Tectonics. Geological Society of London, Special Publication 45: 265–283.
Diaz J, Gallart, Carbonell R (2016) Moho topography beneath the Iberian-Western Mediterranean region mapped from controlled-source and natural seismicity surveys. Tectonophysics 692: 74–85.
Doblas M, López-Ruiz J, Oyarzun R, Mahecha V, Moya YS, Hoyos M, Lunar R (1994) Extensional tectonics in the central Iberian Peninsula during the Variscan to Alpine transition. Tectonophysics 238(1–4): 95-116.
Fillon C, Pedreira D, van der Beek PA, Huismans RS, Barbero L, Pulgar JA (2016) Alpine exhumation of the central Cantabrian Mountains, Northwest Spain. Tectonics 35(2): 339–356.
García-Lasanta C, Oliva-Urcia B, Román-Berdiel T, Casas AM, Gil-Peña I, Sánchez-Moya Y, Mattei M (2015) Evidence for the Permo-Triassic transtensional rifting in the Iberian Range (NE Spain) according to magnetic fabrics results. Tectonophysics 651: 216–231.
García-Lasanta C, Román-Berdiel T, Oliva-Urcia B, Casas AM, Gil-Peña I, Speranza F, Mochales T (2016) Tethyan versus Iberian extension during the Cretaceous period in the eastern Iberian Peninsula: insights from magnetic fabrics. Journal of the Geological Society 173(1): 127–141.
Granja Bruña JL, Vegas R, Sentre Domingo MA, Muñoz-Martín A, Sainz-Maza Aparicio S (2015) Gravity modeling of the lithosphere in the Calatrava Volcanic Province (Spain): geodynamic implications. Journal of Iberian Geology 41(2): 233–252.
Guimerà J (1984) Palaeogene evolution of deformation in the northeastern Iberian Peninsula. Geological Magazine 121(05): 413–420.
Guimerà J, Álvaro M (1990) Structure et évolution de la compression alpine dans la Chaîne Ibérique et la Chaîne côtière catalane (Espagne). Bull Soc Géol Fr 8: 339–348.
Hüsing SH, Oms O, Agustí J, Garcés M, Kouwenhoven W, Zachariasse WJ (2012) On the Late Miocene continentalization of the Guadix Basin: More evidence for a major Messinian hiatus. Geobios 6: 617–620.
Liesa CL, Soria AR, Meléndez N, Meléndez A (2006) Extensional fault control on the sedimentation patterns in a continental rift basin: El Castellar Formation, Galve sub-basin, Spain. Journal of the Geological Society 163(3): 487–498.
Masana E, Villamarín JA, Santanach P (2001) Paleoseismic results from multiple trenching analysis along a silent fault: The El Camp fault (Tarragona, northeastern Iberian Peninsula). Acta Geológica Hispánica 36: 329–354.
Mazzoli S, Helman ML (1994) Neogene patterns of relative plate motions for Africa-Europe: some implications for recent Mediterranean tectonics. Geologische Rundschau 83: 464–468.
Muñoz A (1993) Análisis del Pérmico y Triásico en el subsuelo del tercio noroccidental de la Cordillera Ibérica y áreas adyacentes. PhD Thesis, Universidad Complutense de Madrid, 374 p.
Muñoz-Jiménez A, Casas-Sainz AM (1997) The Rioja Trough (N Spain): tectosedimentary evolution of a symmetric foreland basin. Basin Research 9(1): 65–85.
Muñoz-Martín A (1997) Evolución geodinámica del borde oriental de la Cuenca del Tajo desde el Oligoceno hasta la actualidad. PhD Thesis, Universidad Complutense de Madrid, 320 p.
Muñoz-Martín A, De Vicente G, Fernández-Lozano J, Cloetingh S, Willingshofer E, Sokoutis D, Beekmanl F (2010) Spectral analysis of the gravity and elevation along the western Africa–Eurasia plate tectonic limit: Continental versus oceanic lithospheric folding signals. Tectonophysics 495: 298–314.
Nebot M, Guimerà, JJ (2016) Structure of an inverted basin from subsurface and field data: The Late Jurassic-Early Cretaceous Maestrat Basin (Iberian Chain). Geologica acta 14(2): 0155–177.
Rodríguez-López JP, Liesa CL, Meléndez N, Soria AR (2007) Normal fault development in a sedimentary succession with multiple detachment levels: the Lower Cretaceous Oliete sub-basin, Eastern Spain. Basin Research 19(3): 409–435.
Salas R, Guimerà J, Mas R, Martín-Closas C, Meléndez A, Alonso A (2001) Evolution of the Mesozoic central Iberian Rift System and its Cainozoic inversion (Iberian chain). Peri-Tethys Memoir 6: 145–185.
Simón JL (1983) Tectónica y Neotectónica del sistema de fosas de Teruel. Teruel 69: 21–97.
Simón JL (2004) Superposed buckle folding in the eastern Iberian Chain, Spain. Journal of Structural Geology 26(8): 1447–1464.
Simón JL, Liesa CL (2011) Incremental slip history of a thrust: diverse transport directions and internal folding of the Utrillas thrust sheet (NE Iberian Chain, Spain). Geological Society, London, Special Publications 349(1): 77–97.
Simón JL, Arlegui LE, Lafuente P, Liesa CL (2012) Active extensional faults in the Central-Eastern Iberian Chain, Spain. Journal of Iberian Geology 38(1): 127.
Tugend J, Manatschal G, Kusznir NJ (2015) Spatial and temporal evolution of hyperextended rift systems: Implication for the nature, kinematics, and timing of the Iberian European plate boundary. Geology 43: 15–18.
Valcárcel M, Soto R, Beamud E, Oliva-Urcía B, Muñoz JA, Biete C (2016) Integration of paleomagnetic data, basement-cover relationships and theoretical calculations to characterize the obliquity of the Altomira-Loranca structures (central Spain). Geological Society, London, Special publications 425: 169–188.
Vegas R, Antón L, Gomes A, Medialdea T (2012) Lineaments in the West-Central Hesperic Massif (Portugal and Spain) and their geomorphic and tectonic significance. In: Fernández LP, Fernández A, Cuesta A, Bahamonde JR (eds), Resúmenes extendidos del VIII Congreso Geológico de España. CD anexo a Geo- Temas 13: 1674–1677.
Vegas R, De Vicente G, Muñoz Martín A, Palomino R (2004) Los corredores de fallas de Regua-Verín y Vilariça: zonas de transferencia de la deformación intraplaca en la Península Ibérica. Geotemas 6 (5): 245–249.
Vegas R, Fontboté JM, Banda E (1979) Widespread Neogene rifting superimposed on Alpine regions of the Iberian Peninsula. Proceedings of the Symposium on Evolution and Tectonism of the Western Mediterranean and Surrounding Areas, EGS, Vienna. IGN Special Publication 201: 109–128.
Vegas R, Vázquez JT, Olaiz AJ, Medialdea T (2016) Tectonic model for the latest Triassic-Early Jurassic extensional event in and around the Iberian Peninsula. Geogaceta 60: 23–26.
Villena J, Pardo G, Pérez A, Muñoz A, González A (1996) The Tertiary of the Iberian margin of the Ebro basin: paleogeography and tectonic control. In: Friend PF, Dabrio CJ (eds), Tertiary Basins of Spain: The Stratigraphic Record of Crustal Kinematics, Cambridge Univ Press, E5: 77–82.