AGU100 ADVANCING EARTH AND SPACE SCIENCE

Tectonics

RESEARCH ARTICLE
10.1029/2018TC005204

Key Points:
- The Spanish-Portuguese Central System (SPCS) is a 2,500-m-high Cenozoic intraplate crustal pop-up, with a length of 700 km and a throw of 5 km, with no evidence for tectonic inversion
- The SPCS is northwardly connected to the Pyrenean Orogen. The maximum compression was recorded during the Upper Priabonian to Lower Chattian, with an Upper Tortonian-Gelasian (Betic) rejuvenation
- The presence of the large NE-SW subvertical Messejana-Plasencia Jurassic dyke conditioned a strike-slip displacement in the Messejana-Plasencia (MP) Fault that was compensated throughout thrusts with the same trend by strain partitioning

Correspondence to:
G. de Vicente,
gdv@geo.ucm.es

Citation:
de Vicente, G., Cunha, P. P., Muñoz-Martín, A., Cloetingh, S. A. P. L., Olaiz, A., & Vegas, R. (2018). The Spanish-Portuguese Central System: An example of intense intraplate deformation and strain partitioning. *Tectonics*, *37*, 4444–4469. https://doi.org/10.1029/2018TC005204

Received 26 JUN 2018
Accepted 9 NOV 2018
Accepted article online 12 NOV 2018
Published online 5 DEC 2018

©2018. American Geophysical Union.
All Rights Reserved.

The Spanish-Portuguese Central System: An Example of Intense Intraplate Deformation and Strain Partitioning

G. de Vicente[1,2], P. P. Cunha[3], A. Muñoz-Martín[1,2], S. A. P. L. Cloetingh[4], A. Olaiz[5], and R. Vegas[1]

[1]GEODESPAL Department, Faculty of Geology, Complutense University, Madrid, Spain, [2]Institute of Geosciences, IGEO. CSIC-UCM, Madrid, Spain, [3]MARE, Department of Earth Sciences, University of Coimbra, Coimbra, Portugal, [4]Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands, [5]Repsol Exploration S. A. Madrid, Madrid, Spain

Abstract The intraplate deformation of Iberia during the Cenozoic produced a series of ranges and deformation belts with a wide variety of structural trends. The Spanish-Portuguese Central System is the most prominent feature crossing over the whole of central Iberia. It is a large thick-skinned crustal pop-up with NE-SW to E-W thrusts. However, the 500-km-long left-lateral strike-slip Messejana-Plasencia fault, also NE-SW oriented, bends these thrusts to produce NE-SW local paleostresses close to the fault, which seems to be consistent with a common deformational arrangement. This is also supported by the similar sedimentary infilling characteristics found in the surrounding Cenozoic basins. The moment of the maximum intraplate deformation is registered at the same time in all these basins during the upper Priabonian-lower Chattian. As there are two possible sources for the intraplate compressive stresses, the Pyrenean (N-S shortening) orogen to the north and the Betic (NW-SE shortening) orogen to the south, neither can simply explain both simultaneous movements (NE-SW strike-slip and NE-SW thrusting). The deduced age of the main deformation indicates a Pyrenean origin. In contrast, the concept of strain partitioning between the two types of faults gives as a result an overall north trending compression. Existing data do not support crustal detachment from the Betics neither from the Pyrenees but are consistent with a crustal uplift related to lithospheric folding. The subsequent Betic-related stress field only slightly reworked previously Pyrenean-related structures, except for the Portuguese sector, where tectonic activity occurred mainly in the Upper Miocene.

1. Introduction

The Iberian Peninsula is shaped today by an amalgam of two minor plates, the Iberian Plate and a part of the Alboran Plate, which have been relatively independent during the Cenozoic and have ended up trapped between two major plates, Nubia and Eurasia. This complex tectonic arrangement, together with the different stages of mechanical coupling-decoupling between the involved plates and the different rheology between the east and west of Iberia, has produced a relief pattern and a distribution of characteristic Cenozoic Basin and Ranges Deformation Belts, very different from other areas of the Western Europe Alpine foreland.

Given its size, amount of Cenozoic deformation, and degree of geological knowledge, the interior of Iberia is a true natural laboratory for understanding the interactions between farfield stresses occurring at the plate borders and the formation and evolution of intraplate basins and chains.

Intraplate ranges in the Iberian Peninsula offer a genuine sample of possible structural styles. On the one hand, the presence or absence of sedimentary cover, mainly represented by Mesozoic sediments, produces two sets of well-differentiated ranges. Thus, in the eastern part and fitting with the location of Permo-Triasic and Cretaceous rifting processes, the ranges related to the Iberian Chain were developed with an important tectonic inversion. Although the deformation involves the basement, detachments also appear in the cover. In contrast, the absence of a sedimentary cover and previous extensional structures in the western part excludes tectonic inversion. Therefore, here Cenozoic deformation developed over an area with a more homogeneous rheology, which produced a fairly regular distribution pattern of Cenozoic chains, basins, and deformation belts.

In these ranges without cover (developed in the Variscan Massif), several types of structures can be distinguished depending on the nature of the basement and their position with respect to large lithospheric and crustal folds, which seem to follow their formation. These structures correspond to pop-ups and triangle zones; monoclinal ramps with the formation of a basin in the footwall; basement imbricate thick-skinned and thin-skinned thrust systems; and piggyback basins.

In this study, geological and geophysical data collected from the intraplate deformation of central-west Iberia are used to describe the crustal structure affected by compressive stresses for the full length of 700 km of the Spanish-Portuguese Central System (SPCS). Unlike other ranges of the interior of Iberia (e.g., Iberian Chain), the role of tectonic inversion in the SPCS is negligible (except in the area closest to the Atlantic, containing a Mesozoic record). Because the rates of intraplate deformation in central Iberia during the Cenozoic appear to be much smaller than those typical of plate boundary orogens, the presence of thrusts with a throw up to 5 km provides a very special character for this range. Another interesting aspect of the SPCS structural arrangement is the presence of a major strike-slip fault parallel to the thrusts with a 500-km-long trace: the Messejana-Plasencia (MP) Fault. To simultaneously interpret both types of structures, we explore the concept of strain partitioning in an intraplate tectonic regime subject to lithospheric folding. We also discuss the possible existence of a crustal detachment connecting the studied range with both related orogens: Betics (S) and Pyrenees (N).

2. Methods

The information presented here is derived from structural, geophysical, stratigraphic, sedimentological, geomorphological, and chronological data using a standard approach:

1. *Geomorphological analysis and fault pattern cartography of the studied area*. Available geological maps (IGME, Spain) do not provide adequate information about the Alpine faults. We have interpreted information from previous studies (e.g., de Vicente et al., 2007) improved with additional mapping of new structures.
2. *Determination of the crustal structure of central Iberia from available databases*. The crustal structure beneath Iberia and its continental margins have been explored by a large amount of seismic experiments since the early 1970s, which provided information on seismic wave velocities and the geometry and depth of the main crustal interfaces. Information about physical properties of the crust can be obtained from a number of geophysical techniques including seismic and potential field data analysis. Seismic techniques include wide-angle reflection/refraction seismic profiles, seismic tomography, and receiver functions data. The wide-angle reflection/refraction seismic profiles appear to be the most reliable techniques to constrain the velocity-depth distribution and Moho depth, as the position of the main interfaces and the seismic velocity values are readily inferred from the data through modeling with determinable uncertainties.
3. *Field ground truthing and characterization of Cenozoic sedimentary units* and their relation with tectonic structures. We compiled data from previous studies (e.g., Cunha et al., 2000; de Vicente & Muñoz-Martín, 2012) and established a coherent tectonostratigraphic sequence for the intraplate Cenozoic basins infilling of central-western Iberia.
4. *Literature analysis of absolute dating data* (thermogeochonology) from the main intraplate ranges and a comparison with basin infill data.
5. *Compilation of paleostress analyses of central-western Iberia* and establishment of the active stress field from earthquake focal mechanisms (e.g., de Vicente et al., 2008).
6. *Final integration, analysis, and interpretation of data*.

3. Geodynamic Setting

During the Cenozoic, the Iberian Peninsula experienced an intense intraplate deformation as a result of stress transmission from its successive active borders (first the N border and later the SW border). Therefore, since the middle Campanian (Late Cretaceous), the northern border of Iberia transmitted a N-S compressive stress, leading to the progressive genesis of the E-W-oriented Cantabrian-Pyrenean orogen at the north. Since the Lutetian (Middle Eocene), southward sedimentary basins were formed by lithospheric folding (Cloetingh et al., 2002; Muñoz-Martín et al., 2010; Tejero et al., 2010), also W-E to WSW-ENE oriented (e.g., the Cenozoic Mondego basin aligned with the Duero basin, the Lower Tagus basin aligned with the Madrid basin, etc.; e.g., Cunha, 1992a; de Vicente et al., 2011; de Vicente & Vegas, 2009; Pais et al., 2012), reflecting a well-distributed deformation (de Vicente & Vegas, 2009).

During the Lutetian to early Chattian, the N-S shortening reached a maximum deformation within the northern border of Iberia (Vergés, 1999). However, it was during the late Chattian to Burdigalian (Late Oligocene to Early Miocene) that it reached a maximum within the Iberian interior, clearly registered by coeval deformation in the Iberian Chain (to the E; de Vicente et al., 2009) and in the Lower Tagus basin (to the W; e.g., Curtis, 1999). Apatite fission track data show an important cooling event in the Cameros area between 31 and 40 Ma (del Río, 2009), also registered in the SPCS (Spanish sector; De Bruijne & Andriessen, 2002) and in the westernmost part of the Cantabrian Pyrenees (Fillon et al., 2016). At the same time, a NW-SE trending compressional stress field is registered in the Spanish sector of the SPCS.

The continuation of the movement toward NW of the African plate led to the climax of intraplate compression in Iberia, probably already oriented NNW-SSE to NW-SE, initiated at ca. 9 Ma (middle Tortonian; Dewey et al., 1989). This caused the renewed uplift of the Central System (Spanish, Portuguese onshore and also offshore; e.g., Cunha, 1992a; De Bruijne & Andriessen, 2002; Ribeiro et al., 1990) and of the Mountains of NW Portugal, mainly by reverse faulting and thrusting (Cunha, 1992a; Cunha et al., 2000). The Betic orogen was able to transfer NW-SE-oriented compressive stresses to its foreland for a shorter period of time (ca. 9–3.7 Ma), probably because of the fast rollback process related to the subduction of the Alborán domain (Spakman & Wortel, 2004) and the subsequent crustal thinning in the early Miocene, which resulted in the subsidence of much of the region below sea level developing the Alborán basin (Comas et al., 1999). During this tectonostratigraphic stage of deformation, NNE-SSW fault zones were compressively reactivated as left-lateral strike-slip faults with significant vertical displacement, producing local sedimentary basins and uplifted areas along the fault trace. As a consequence, since middle Tortonian, the Iberian intraplate ranges and the Cenozoic sedimentary basins were also deformed by the newly oriented NW-SE compressive stresses related to the emplacement of the Alborán Domain (Betics) to the south, resulting in several tectonostratigraphic events being produced. These are recorded by allostratigraphic units, separated by sedimentary discontinuities related to the successive tectonic phases (Calvo, 2004; Calvo et al., 1993; Cunha, 1992a, 1992b; Pais et al., 2012).

During the last ca. 3.7 Ma, the registered active stresses in front of the Betics have been extensional (de Vicente et al., 2008), but in the SW corner of Iberia, compressive active stresses and reverse focal mechanisms still prevail and point to a Quaternary WNW-ESE-oriented compression (e.g., Cabral, 1995, 2012; Cunha et al., 1993, 2008; de Vicente et al., 2008; Sequeira et al., 1997).

3.1. Compatibility Between Main Structural Trends and Stress Directions

As a result of the successive intraplate stresses, the Alpine mountain ranges and deformation belts of Iberia show a variety of structural trends and related paleostress fields (e.g., de Vicente et al., 2011; Figure 1). Thick-skinned tectonic related thrusts dominate, namely,

- E-W thrusts: Toledo Mountains (3a), Badajoz Thrust (3b), and two domains within the Iberian Chain, Cameros-Demanda (2a), and Montalban (2b).
- NE-SW thrusts: Central System (comprising two sectors, Spanish, 1a, and Portuguese, 1b) and the Catalan Coastal Ranges (4).

A single N-S compression can directly explain the structures of (A). The Altomira Range (2c) has been interpreted as a thin-skinned tectonics escape structure toward the W, under constrictive conditions of the deformation with a regional N-S shortening (Muñoz-Martín, 1997). This stress orientation can also explain the left-lateral movement of (5).

For the Iberian Chain, the intense anisotropy produced in the upper crust during the Permian-Triassic and Cretaceous rifting processes gave rise to partitioned, separate, deformational domains of pure shear and simple shear during the Cenozoic inversion of previous tectonic structures. Structural weakness zones, mainly previous normal faults, were capable of partial accommodation of the Alpine deformation. Large E-W extensional faults originated during the Cretaceous at Cameros-Demanda and Montalban sectors of the Iberian Chain were partially inverted as thrusts (2a, 2b), whereas Permo-Triassic NW-SE normal faults gave rise to a wide transpressive belt with a clear strain partitioning (2e) (de Vicente et al., 2009).

For (1a), (6), and (4), the structural behavior is quite different. For the majority of the Cenozoic, N-S- to NNW-SSE-oriented intraplate stress fields led to distinct tectonic deformations controlled by the direction of the active faults: (i) the single MP fault (ca. NE-SW, 6) more than 500 km long, which moved as a pure

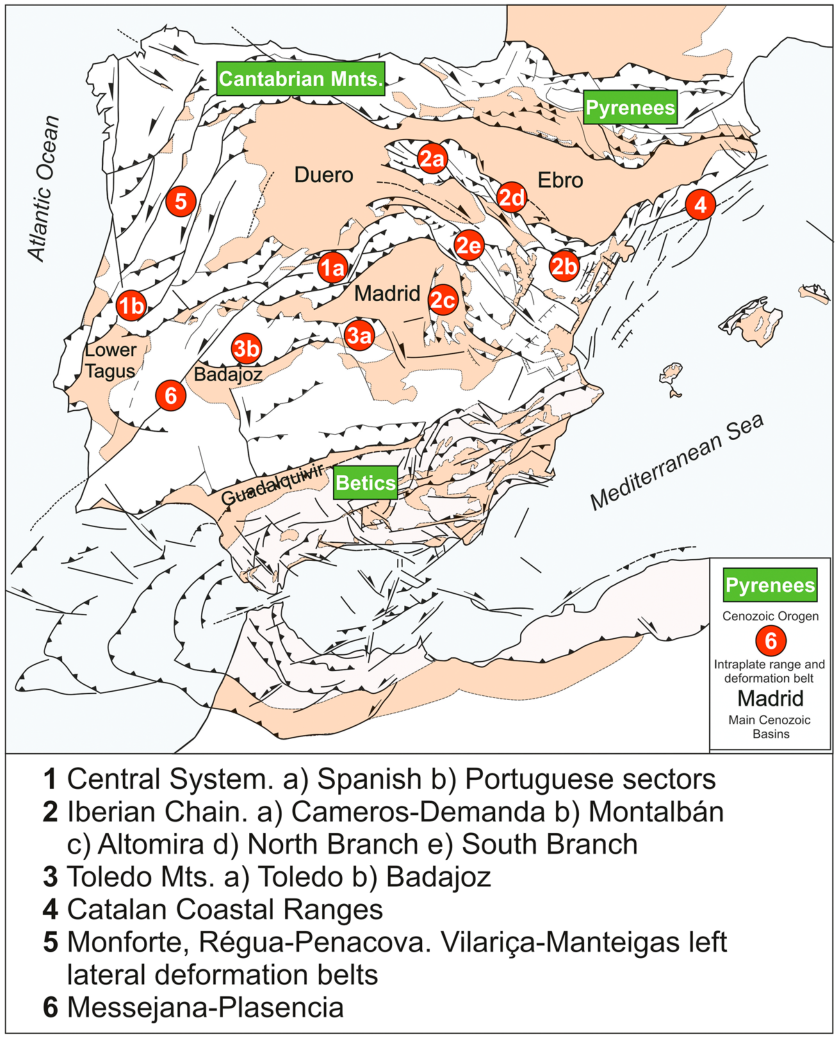

Figure 1. Identification of the main Cenozoic tectonic systems in Iberia, corresponding to significant topographic relief, and adjacent sedimentary basins.

left-lateral strike-slip fault; (ii) the ENE-WSW to NE-SW thrusts that uplifted the SPCS accumulating an intense pure shear deformation, mainly concentrated in the SCS (Madrid Basin) Thrust (more than 5 km of vertical throw over the Madrid Cenozoic Basin); (iii) important NNE-SSW Late Variscan fault zones (5) located in northern mainland Portugal were reactivated as left-lateral strike-slip deformation belts, sometimes with significant local and regional vertical displacements (Plateaus and Mountains of Northern Portugal and Leon Mountains in Spain). This tectonic pattern resembles more than occurring in obliquely convergent plate borders with strain partitioning than what is observed in transpressive belts.

4. Results

4.1. The SPCS

This intraplate crustal pop-up can be defined as a roughly ENE-WSW range (alternatively oriented E-W and NE-SW in Spain and NE-SW in Portugal; Figure 2). Being up to 2,500 m high, it constitutes the most prominent topographic elevation in the interior of the Iberian Peninsula. It is more than 700 km long, from the Iberian Chain to the Atlantic border in Portugal, comprising the Portuguese Central Range (Gardunha, Estrela, Açor, and Lousã Mountains) and the Western Mesozoic Terrains (Mesozoic onshore terrains uplifted during the Cenozoic).

10.1029/2018TC005204

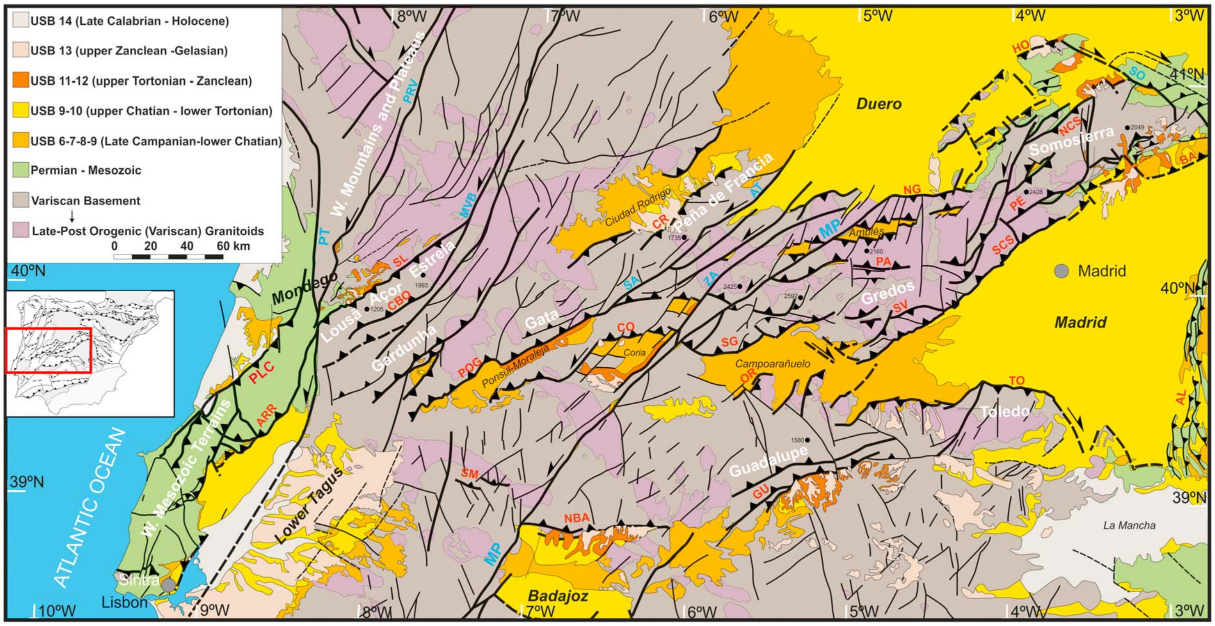

Figure 2. Identification of the main Cenozoic faults, Cenozoic sedimentary basins (Mondego, Duero, Lower Tagus, Badajoz, and Madrid), and general stratigraphy. Variscan metamorphic basement = phylites and metagreywackes, Late-Post Orogenic granitoids = mainly granites, Permian to Mesozoic = sandstones/siltites and limestones/marls, Cenozoic = mainly sandstones and conglomerates. Cartography of the upper Campanian to Quaternary allostratigraphic units (UBS) is represented. Thrust faults (referenced in red): BA = Baides, HO = Honrubia, NCS = North Central System, SCS = South Central System, PE = Peñalara, NG = North Gredos, PA = Paramera, SV = San Vicente, SG = South Gredos, TO = Toledo, OR = Oropesa, GU = Guadalupe, NBA = North Badajoz, CO = Coria, SM = San Mamede, POG = Ponsul-Gata, CR = Ciudad Rodrigo, CBO = Cebola-Bogas, SL = Seia-Lousã, PLC = Pombal-Leiria-Caldas da Rainha, ARR = Arrife. Strike-slip faults (referenced in blue): SO = Somolinos, MP = Messejana-Plasencia, ZA = Zapardiel, AT = Alba de Tormes, SA = Sangusín, MVB = Manteigas-Vilariça-Bragança, PRV = Penacova-Régua-Verín, PT = Porto-Tomar.

The SPCS separates two sets of Cenozoic continental basins (Mondego and Duero basins, to the north; Madrid and Lower Tagus basins, to the south). The contact of the SPCS with these basins is always a major thick-skinned tectonics-related thrust (Variscan basement over Cenozoic sediments; SCS, NG, SG, and HO in Figures 2 and 3), which clearly indicates the compressive origin of this range with double vergence. In the Spanish sector (that includes the Somosierra, Gredos, and Gata-Sierra de Francia Mountains), the southern thrust seems to accumulate a larger displacement, whereas in the north, the tectonic structure appears as a series of imbricate thrusts with smaller individual displacements (de Vicente et al., 1996, 2004; Ribeiro et al., 1990; Vegas et al., 1990). The Gredos and the Gata-Sierra de Francia ranges are separated by the MP fault.

The eastern Portuguese sector (Portuguese Central Range) comprises to two main NE-SW-directed basement uplifts of the Lousã-Açor-Estrela (1,990 m) and Gardunha (1,227 m) ranges, which are separated by NE-SW faults. The compressive deformation appears to be mainly concentrated in the NW and SE borders, in two thrusts corresponding to the Seia-Lousã (SL) fault and to the Ponsul-Gata fault (Figure 2).

The closest area to the east of the MP fault (Gredos Mountains) presents a roughly E-W (N80°) direction, different from the other sectors. It is composed of three longitudinal pop-up-like basement elevations with thrusted triangle zones, some of them filled by Cenozoic sediments (e.g., the small Amblés Basin).

The Spanish sector of the SPCS terminates to the east against the Iberian Chain, interpreted as a crustal right-lateral tear deformation belt of the Central System (de Vicente et al., 2009).

The Portuguese Central Range is roughly limited by the Manteigas-Vilariça-Bragança (MVB) fault (to the east) and by the Penacova-Régua-Verín (PRV) fault (to the west). There is an apparent relationship between the south terminations of these strike-slip left-lateral faults and the Portuguese Central Range and the Western Mesozoic Terrains (Montejunto-Sintra reliefs) crustal pop-ups. They apparently draw a compressive horsetail structure (Figure 2) that seems to have transferred the N-S (Pyrenean) compressive deformation southward its foreland (Vegas et al., 2004). This global arrangement supports the idea of a N-S shortening direction as the initial development of the SPCS during the Oligocene-Miocene, which is related to the Cantabrian

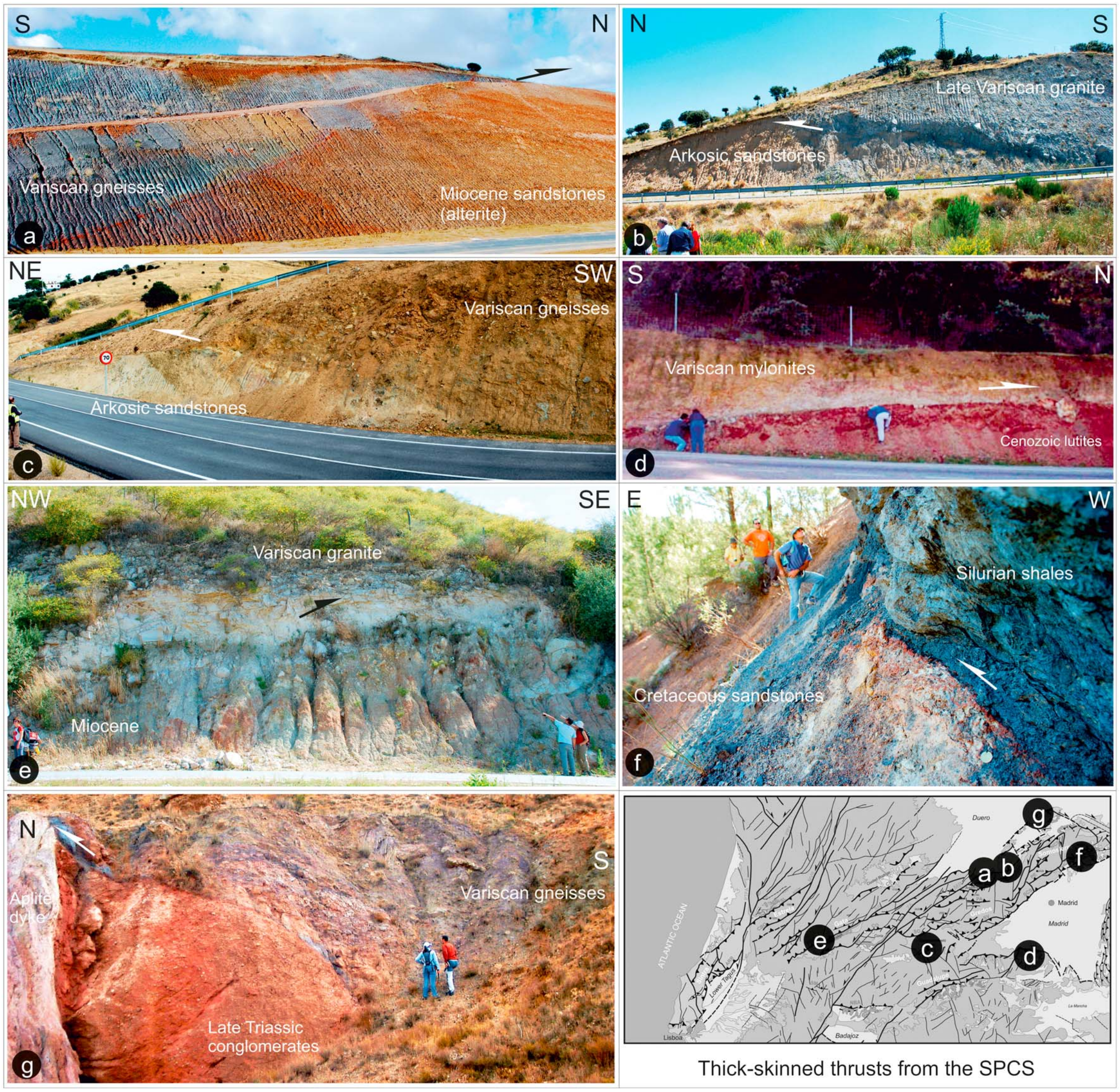

Figure 3. Examples of thick-skinned tectonic-related thrusts from the Spanish Portuguese Central System (SPCS). (a) NG north of Avila at Avila-Salamanca A-50 highway. (b) NG at Zarzuela del Monte, Avila. (c) OR at Oropesa, western Madrid basin. (d) TO at Toledo city. (e) POG at Idanha a nova, Ponsul-Moraleja basin. (f) SCS at Beleña de Sorbe, western Madrid basin. (g) HO at Fuentenebro, Duero Basin. The names of the faults are given in Figure 2.

Mountains-Pyrenees orogen. The initial deformation in the Montejunto anticline and the Arrábida range (Western Mesozoic Terrains) was related to a roughly N-S shortening (Curtis, 1999) dated as 17 Ma (Burdigalian; e.g., Kullberg et al., 2000). This phase occurred prior to the development of the NE-SW thrusts, which can be considered as the PRV or Porto-Tomar (PT) strike-slip terminations later reactivated by the NW-SE Betic compression. Nevertheless, the overall ENE-WSW structural trend of the Arrábida chain points more to a NNW-SSE shortening direction for a significant part of the Cenozoic.

In the Spanish sector of the SPCS, Apatite Fission Track (AFT) data suggest that the most accelerated cooling events can be grouped into four periods (De Bruijne & Andriessen, 2002): Middle to early Late Eocene 43 ± 7 Ma, Early to early Late Oligocene 30 ± 4 Ma, Early Miocene 19 ± 3 Ma, and Late Miocene to present day 5 ± 5 Ma.

4.2. Crustal Structure of Western Central Iberia

The most accurate and complete databases to define the Iberian crustal geometry are the deep sounding seismic profiles and teleseismic receiver function compilations completed by Díaz and Gallart (2009), Diaz et al. (2016), Dündar et al. (2016), Mancilla and Diaz (2015), and Mancilla et al. (2015). Those targeted

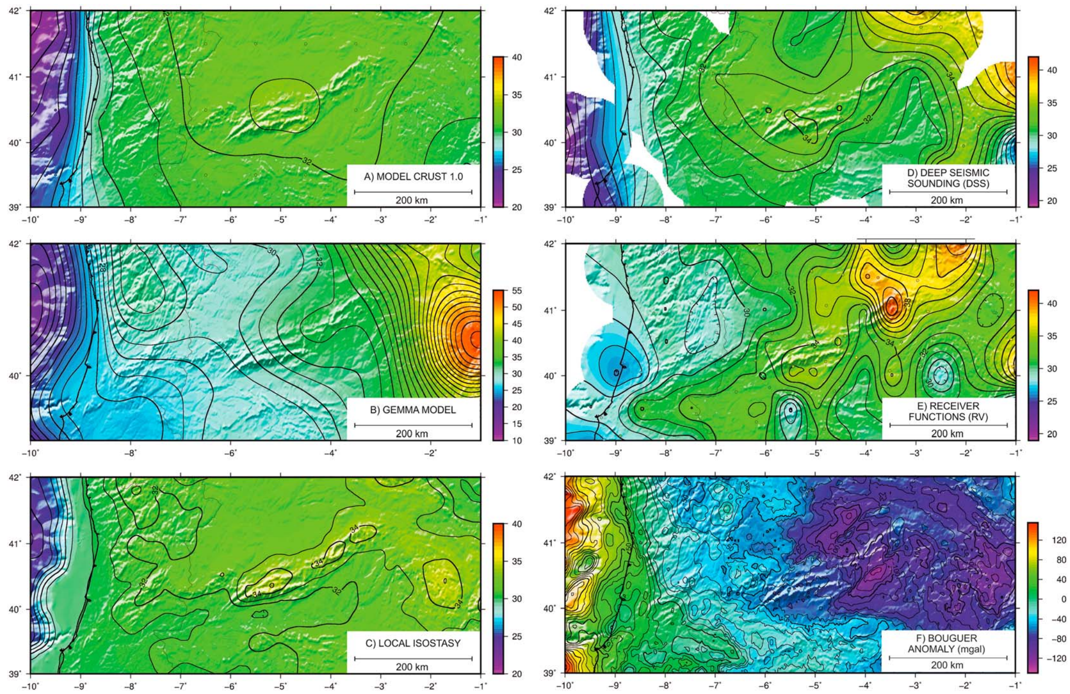

Figure 4. Moho depth maps interpolated or resampled to a 5 × 5-min grid (contours each 1 km), obtained from (a) CRUST1.0 model (Laske et al., 2013), (b) GEMMA model (Reguzzoni & Sampietro, 2015), (c) gravity data and local isostasy (Muñoz-Martín et al., 2004), (d) Deep Seismic Soundings (Díaz et al., 2016), (e) receiver functions studies (Mancilla & Díaz, 2015), and (e) Bouguer anomaly (mgals).

studies on the Iberian crust are complemented through other global databases, which provide the geometry of the crust in a continuous way worldwide. Of these, the best known are the CRUST 1.0 (Laske et al., 2013) and GEMMA (Reguzzoni & Sampietro, 2015). The CRUST 1.0 model (Laske et al., 2013) provided a 1° by 1° grid of the Moho based on a seismic tomography model from surface wave, free oscillation, and body wave travel times of the arrival times in earthquake catalogues. The GEMMA model (Reguzzoni & Sampietro, 2015) is based on satellite gravimetric gradiometry data inversion constrained by seismic data of deep refraction and sedimentary fill thickness with a final resolution of 0.5° × 0.5° (Figures 4a, 4b, 4c, 4d, and 4e).

The main problems when using these data to interpret the Alpine structure of western Iberia include the following:

(a) There are few and sparse deep seismic refraction profiles in the interior of the Iberian Peninsula.
(b) Deep seismic profiles with E-W or NE-SW orientations are suitable for analyzing the structure of the Iberian margin or the Variscan Orogen, but they do not allow the analysis of the main Alpine structures recognized in the field, which have orientations from E-W to NE-SW.
(c) The crustal thickness data based on receiver functions have been obtained mainly from the seismic stations of the TOPOIBERIA project (Mancilla & Diaz, 2015), along an approximately regular mesh of 60 × 60 km. These authors provide a continuous Moho geometry with low resolution (1 datum every 60 km or more) obtained from the 1D models of V_p and V_s. However, topography wavelength is narrower than seismic station separation. Therefore, the crustal thickening inferred below the higher Alpine reliefs might be misestimated. Although it does not deviate much from the deep sounding seismic data, it presents a more irregular distribution when compared to the topography. Thus, the presence of specific data in the Guadarrama area with a crustal thickness of >40 km (Figure 4e) is biased to the general pattern. In the Portuguese sector, the Moho database from Diaz and Mancilla is augmented by adding the results of Dündar et al. (2016), which allow a clearer relationship with first-order geological features such as the Gata Sierra (Figure 5).

Gravimetric data (Figure 4f) make it possible to establish a continuous geometry of the Moho by inverting local isostatic models or combining steady-state thermal analysis (Muñoz-Martín et al., 2004; Torne et al.,

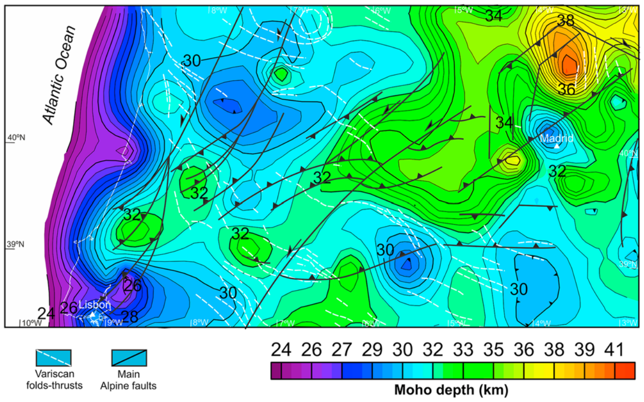

Figure 5. Moho depth of western central Iberia after Diaz et al. (2016) and Dundart et al. (2016). Main faults are also shown. Approximately same area as Figures 2 and 4.

2015). Unfortunately, local isostatic behavior is a simplification, as shown by several studies, because of the presence of flexural deformations of the crust and/or the Iberian lithosphere (Cloetingh et al., 1999, 2002; Muñoz-Martín et al., 2010). So, assuming that range compensation occurs vertically is very simplistic. Also, thermal conductivity and radiogenic production data are taken together, which is also very simplistic. Finally, the development of 2D gravity models that adjust the large wavelengths of gravimetric anomalies to the geometry of the Moho allow us to analyze this geometry across the main chains (de Vicente et al., 2007; Pous et al., 2012). These studies reveal the presence of a cortical thickening below the Alpine ranges between 33 and 36 km (Guadarrama and Gredos ranges).

Considering all these limitations, recent Moho maps superimposed on the main faults (Figure 5) allow us to relate some of the most important Alpine structures to variations in Moho geometry in the SPCS surroundings.

Each of the crustal models involves crustal thicknesses in the SPCS ranging from 32 to 35 km, with the greatest thickness related to the Gredos area. Continuous models show this thickening with an orientation parallel to the main reliefs (ENE-WSW). These thickenings have been interpreted as a result of brittle deformation in the upper crust and by ductile thickening in the lower crust (de Vicente et al., 2007). In this way, in the interior of the Iberian Peninsula, the Moho very gently reflects the main intraplate Alpine reliefs. Westward of Gredos, thickening is not observable anymore. A relatively flat area around 28–30-km depth is developed as thickening ceases and gives way to a crust with a minimum thickness of between 28 and 30 km, corresponding to the surface development of the basins of Ciudad Rodrigo and Ponsul-Moraleja. In the Serra da Estrela and Sierra de Gata ranges, there is some crustal thickening, but it does not seem to exceed 30–32 km. The transition to the western Mesozoic cover is shown as a crustal thinning zone with thicknesses of less than 28 km.

The NNE-SSW left-lateral strike-slip deformation belt of western Iberia, and its related horsetail splays, is also clearly depicted as a relatively shallow Moho depth bordered by two relative highs with a short wavelength. The same situation seems to occur along the MP Fault (Figure 5).

4.3. Crustal Cross Sections of Western Central Iberia

One of the most important features of the SPCS is that it is not an inverted range. Only in the westernmost part (Western Mesozoic Terrains) some Mesozoic normal faults of the Lusitanian basin (Rasmussen et al., 1998) resulted in tectonic inversion (Arrife and Pombal-Leiria-Caldas da Rainha; Figure 6e). The Somolinos fault (Figure 2) was also an important Permo-Triassic normal fault but is considered as the limit between the SPCS and the Iberian Chain, where Cenozoic inversion is ubiquitous. Thus, the presence of the MP dyke and the large Post-Late Variscan batholiths of central Iberia could have played an important role in the nucleation of the SPCS since its trend is almost perpendicular to the Variscan grain (Figures 2 and 5). Although overall the SPCS is a double vergence crustal pop-up, the main tectonic transport is southward directed. This is shown by the fact that in the eastern part, the Southern Thrust (SCS; Figure 2) accumulates the maximum displacement (Figure 6a) but also because the Portuguese Central Range and the Western Mesozoic Terrains are horsetail splays of left-lateral faults (PT, PRV, and MVB) that transfer the Pyrenean deformation toward the South.

The style of deformation of the sector north of the Madrid Cenozoic basin is quite different from that of the central part of the SPCS. Here the range has an orogenic wedge-like structure, with a series of imbricated thrusts toward the Duero basin. The detachment levels are not within the sedimentary cover but in the metamorphic Variscan basement, which is different to the west with a mainly granitic basement. Along the SCS, back thrusts and triangle zones are very frequent, while to the NE, pop-ups predominate as far as the NCS, where the maximum crustal thickness is reached in the SPCS (41 km; Figures 5 and 6a; Diaz et al., 2016).

Regular triangle zones and pop-ups are characteristic of Gredos (Figure 6b), while to the north, the MP and ZA faults seem to draw a crustal positive flower structure close to the border of the Duero Basin. This cross

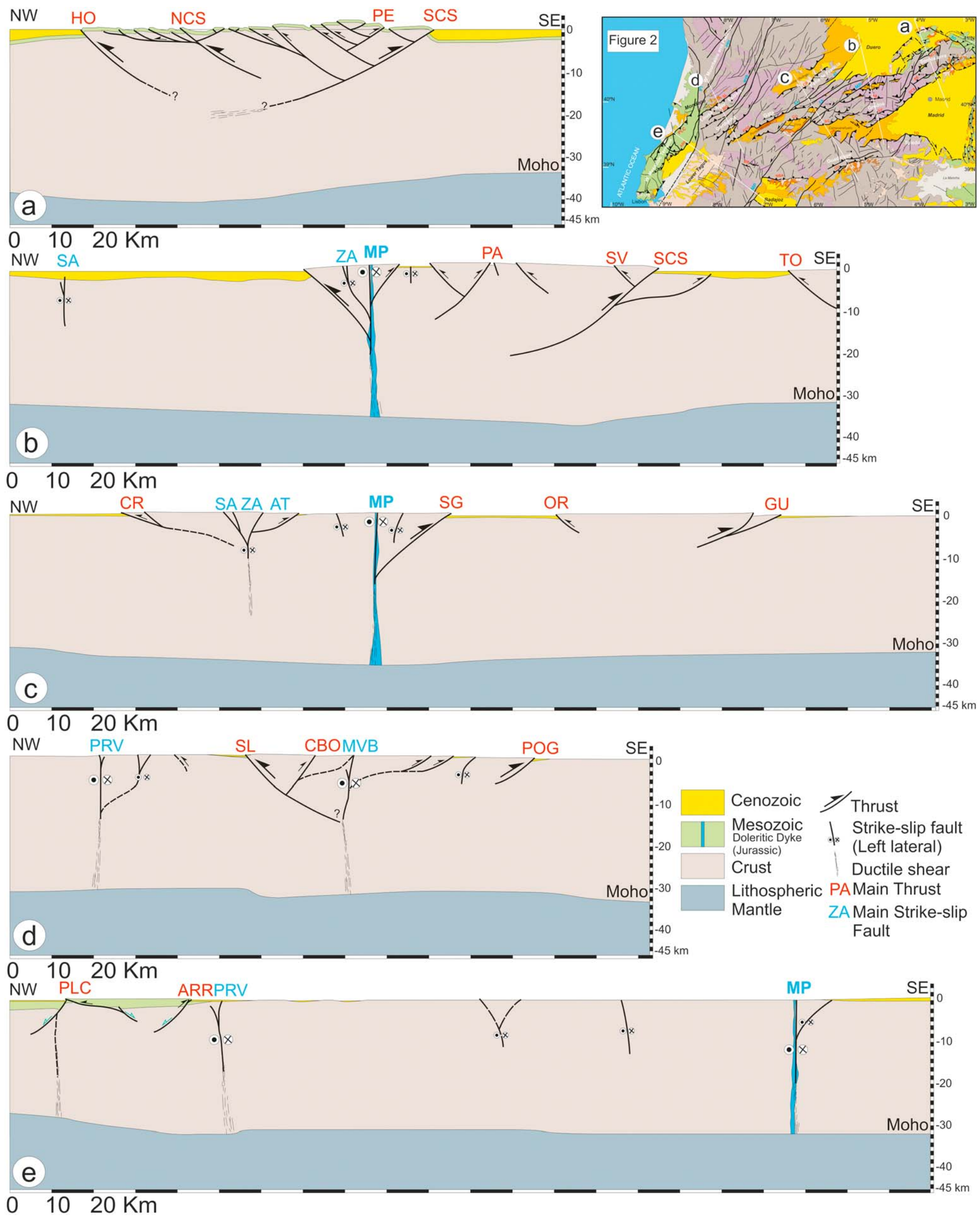

Figure 6. Lithosphere-scale cross sections of western central Iberia. Sections are represented at equal horizontal and vertical scale. Thrust faults (in red): BA = Baides, HO = Honrubia, NCS = North Central System, SCS = South Central System, PE = Peñalara, NG = North Gredos, PA = Paramera, SV = San Vicente, SG = South Gredos, TO = Toledo, OR = Oropesa, GU = Guadalupe, NBA = North Badajoz, CO = Coria, SM = San Mamede, POG = Ponsul-Gata, CR = Ciudad Rodrigo, CBO = Cebola-Bogas, SL = Seia-Lousã, PLC = Pombal-Leiria-Caldas da Rainha, ARR = Arrife. Strike-slip faults (in blue): SO = Somolinos, MP = Messejana-Plasencia, ZA = Zapardiel, AT = Alba de Tormes, SA = Sangusín, MVB = Manteigas-Vilariça-Bragança, PRV = Penacova-Régua-Verín, PT = Porto-Tomar.

section coincides and fits well with constraints from a recent magnetotelluric profile (Pous et al., 2012). In this case, the thickened crust is located to the south, below the SCS thrust.

Figure 6c shows a section crossing from the Ciudad Rodrigo to the Guadalupe thrusts, both with two imbricate fans and opposite tectonic transport. The SA-ZA-AT left-lateral fault system draws a palm tree like structure. The terminations of the Ponsul-Gata and Southern Gredos thrusts must be connected at depth with this deformation belt and with the MP fault, respectively. Here the Moho depth is larger just below the MP fault. The same kind of connection must exist between the MVB fault and the Portuguese Central Range

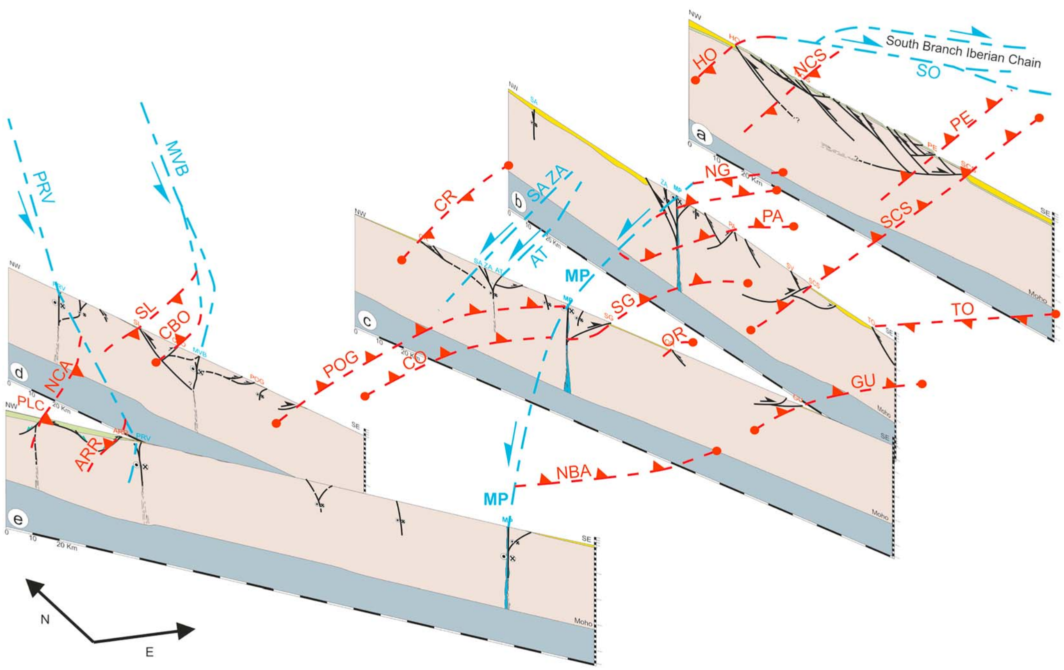

Figure 7. 3D reconstruction of lithospheric main Cenozoic faults of western central Iberia (for comparison, crustal cross sections represented in Figure 6 are also shown here).

thrusts (SL and Cebola-Bogas; Figure 6d) since they form a horsetail splay structure with a crustal thickening beneath the SL thrust. There is a smooth increase of the Moho depth (1 km; Figure 5) along the PRV left-lateral fault that must be related to a positive flower structure. This arrangement could explain some of the sedimentary infilling characteristics of the western sector of the Duero Basin.

In the westernmost section (Figure 6e), the crust is thickened to the west of the junction of the PT and PRV faults. The ARR thrust is a clear example of a partially inverted Mesozoic normal fault of the Lusitanian Basin. Nevertheless, the Mesozoic thickness increases to the west of the Pombal-Leiria-Caldas da Rainha thrust and cannot be explained as an inversion of a west dipping normal fault. In this case, this supports the existence of a cover detachment nucleated on a different normal fault to the east. A 3D reconstruction of all these cross sections is presented in Figure 7.

4.4. Cenozoic Tectonostratigraphic Stages and Episodes of Deformation

The stratigraphic history of the successive phases of compression between Iberia, Europe, and Africa is recorded in the sedimentary basins of Iberia in the form of units bounded by unconformities. The unconformity-bounded units recognized in the latest Cretaceous and Cenozoic record are as follows (e.g., Antunes et al., 1995; Calvo et al., 1993; Cunha, 1992a; Cunha et al., 2000; Figure 8):

- The upper Campanian to lower Ypresian tectonostratigraphic stage is recorded in western and central Iberia as the allostratigraphic units UBS5 and UBS6, which comprise recycled fluvial sedimentation and peridiapiric alluvial fans, and also by tectonic (N-S, NE-SW, and NW-SE with steeply dipping faults) and magmatic activity. This stage records the beginning of the N-S compression (Pyrenean).
- The Lutetian to lower Chattian tectonostratigraphic stage is represented by the UBS7 and UBS8, the sedimentary record of which can be interpreted as low-gradient alluvial fans and large braided rivers. The main lithologies are poorly sorted green arkoses and conglomerates. These two allostratigraphic units record the intensification of the N-S compression, expressed by two tectonic events ("Pre-maximum Pyrenean"—ca. 47 Ma; "Pyrenean"—ca. 36 Ma) in a general setting of lithosphere folding (E-W to ENE-WSW trending) and endorheic weak drainages. The UBS8 (upper Priabonian to lower Chattian; Figure 9a) seems to record the maximum of Pyrenean compression in central Iberia.
- The upper Chattian to lower Tortonian tectonostratigraphic stage is represented by the allostratigraphic units UBS9 and UBS10, which comprise fluvial orange arkoses and green silts, but also lacustrine clays

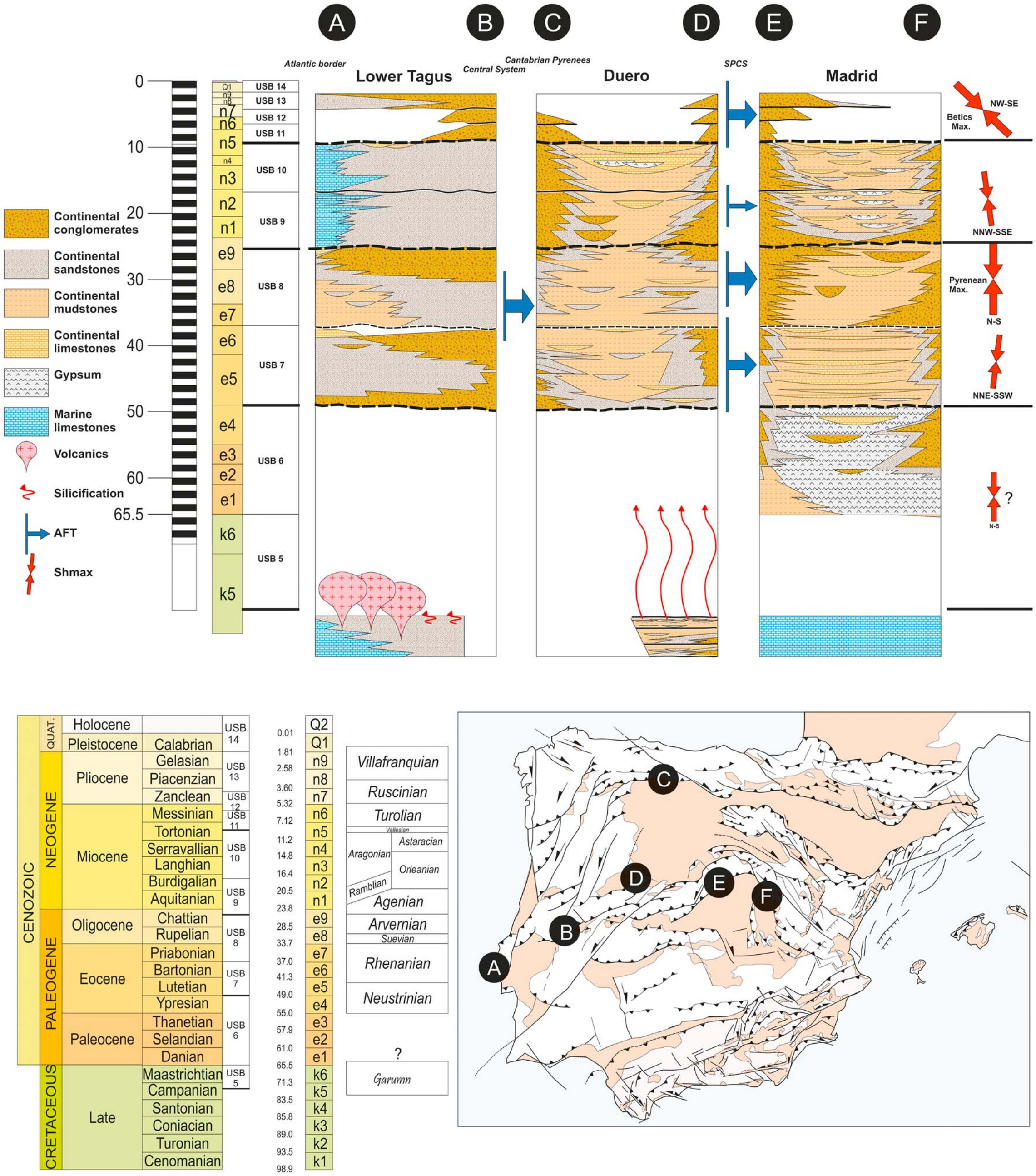

Figure 8. Synthesis of the sedimentary infill of the Lower Tagus, Duero, and Madrid Cenozoic basins. Allostratigraphic units according to Cunha (1992a, 1992b).

and limestones (in the endorheic basins of central Iberia: Duero, Madrid, and Badajoz). These two allostratigraphic units record an intense N-S to NNW-SSE compression, expressed by a main tectonic event (called "Neocastillian" in Spain and "Arrábida" in Portugal—17 Ma). In the Arrábida Chain, there is also a renewed tectonic event at 7.5 Ma. It generated active faulting, mainly as NNE-SSW left-lateral strike-slip faults and ENE-WSW reverse faults.

- The upper Tortonian to Present tectonostratigraphic stage records the maximum of Betic intraplate deformation, related to a dominantly NW-SE-oriented compression. Several tectonic events and allostratigraphic units were identified: UBS11 (upper Tortonian to Messinian): poorly sorted green to brown alluvial fan gravels (clasts of metagreywackes and phyllites) and silty clays; UBS12 (upper Messinian to lower Zanclean): poorly sorted red alluvial fan gravels and silts with clast composition dominated by white quartz and

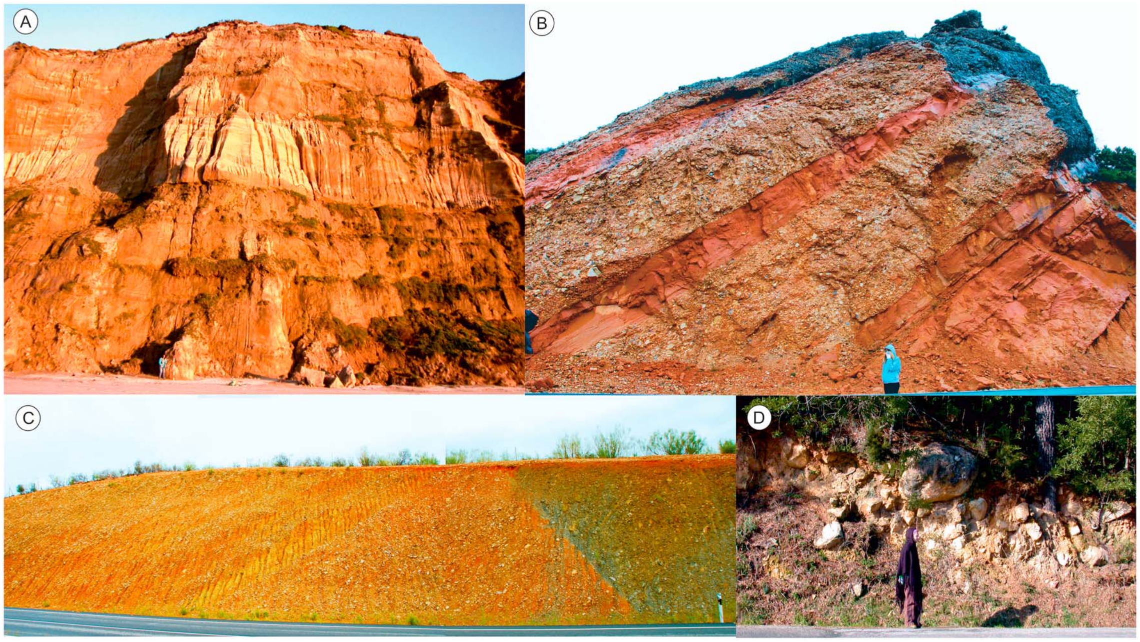

Figure 9. (a) Fluvial deposits of the UBS7 (Lutetian to Bartonian) and the UBS8 (Priabonian to Chattian) at Vale Furado coast (western central Portugal), Mondego Cenozoic basin. (b) UBS8-9 at the S border (easternmost area) of the SCS. Record of the upper Chattian to lower Aquitanian tectonostratigraphic stage, the main Pyrenean stage of compression (N-S). (c) UBS11-12 at the E border of the Coria basin. Upper Tortonian-Zanclean. The alluvial fans are thrusted by Variscan gneisses. (d) Proximal alluvial fan deposits of the UBS13 (uppermost Zanclean to Gelasian), containing heterometric boulders of quartzite and weathered clasts of phyllite. This outcrop is located near the faulted contact with the Variscan basement, produced by the Lousã-Seia thrust, at Mondego Cenozoic basin, Portela de Góis (central Portugal).

metagreywackes (Figure 9c); UBS13 (uppermost Zanclean to Gelasian): heterometric ochre alluvial fan gravels, containing large quartzitic boulders in areas fed by resistant ridges of Ordovician quartzites, linked laterally to large gravelly and sandy rivers and marine siliciclastic (Figure 9d); UBS14 (Pleistocene to Holocene): entrenched valleys and terrace staircases generated by the fluvial incision stage, with Pleistocene terrace deposits, colluviums, eolian sands, but also Holocene modern river and coastal sediments.

A characteristic feature of the Cenozoic basins of central Iberia (Duero and Madrid basins) is the presence of progressive unconformities at their edges, reflecting the syn-tectonic nature of the Lutetian to lower Chattian tectonostratigraphic stage. As an example, the Beleña de Sorbe-Torremocha de Jadraque unit (Portero & Olivé, 1983) represents a marked change in the infilling of the Madrid basin, with a notable increase in alluvial fan deposition. This unit has a thickness of over 900 m and becomes more terrigenous toward the top, with decreasing number of marl layers and an increasing presence of relatively thick layers of channel bodies and conglomerates (between 50 and 175 m thick; Figure 9b). These materials indicate an intense tectonic activity. The upper part of the unit is eroded or covered by more recent sediments that are clear syn-tectonic facies (50 m thick), forming a progressive unconformity together with the first Neogene unit (Calvo, 2004). The sediments are red lutites with layers of conglomerate and sandstone. This facies distribution has led to discrepancies in findings by different authors when assigning certain subunits to the Paleogene or to the Neogene (Torres et al., 2006).

Considering the available AFT data from the SPCS (De Bruijne & Andriessen, 2002) as well as from the Cantabrian Mountains (Fillon et al., 2016; Figure 8), a time delay is suggested between the uplift climax in the Cantabrian Mountains and in the SPCS (respectively, 39–29 and 34–26 Ma). However, it is expected that the deformation transmission from the main orogen to its foreland was not instantaneous, as documented by analogue modeling results for the intraplate deformation of Iberia (Fernández-Lozano, 2012; Fernández-Lozano et al., 2011). The morphology of the Late Cenozoic alluvial fans all over the SPCS is partially preserved, and they do not constitute a continuous unit. They are well represented along the piedmonts of the Toledo Mountains, Guadalupe thrust, Ponsul-Gata thrust, SL thrust, Coria basin margin faults (Figure 9), and in the area close to the Iberian Chain (SCS, NCS, and HO). Three different subunits can be widely recognized (UBS11, UBS12, and UBS13). The lower alluvial fan unit (UBS11) has an average thickness of 40 m (reaching 100 m at the eastern SCS) and consists of heterometric gravels with a clay matrix, comprising clasts of schist, gneiss, and granite (with accessory quartzite and quartz clasts), passing laterally into sands and red clays. The UBS12 is similar to the lower unit (albeit with an appreciable increase in the proportion of quartz and quartzite boulders). The UBS13 alluvial fan deposits are very thick (reaching 200 m) at the edges of the basin thrusted borders, onlapping all the previous units; the unit is coarser and the clasts are dominantly of quartzite. Altogether, the alluvial fan deposits also show smooth folds and are faulted (Figure 9c). The recent uplift of the Portuguese Central Range and the Gata and Guadalupe ranges is also recorded by these sediments (Cunha, 2008; Cunha et al., 2000).

From the AFT analysis (Fillon et al., 2016), there is no evidence of significant uplift in the Cantabrian Mountains during upper Tortonian to present, whereas in the Betics, the main recorded uplift was dated at 16.6 ± 0.8 Ma (Andriessen & Zeck, 1996). In the SPCS, the last evidenced uplift is Late Miocene to present day (5 ± 5 Ma; De Bruijne & Andriessen, 2002). This pattern of time delay seems to be similar to that observed during the Pyrenean orogenic pulse. It also supports the concept of a Betics origin for the UBS11-12-13 sedimentation.

4.5. The MP Fault and Associated Cenozoic Sedimentary Record

The MP is nucleated on an Early Jurassic dyke (203 ± 2 Ma; Dunn et al., 1998) that has been linked to a large magmatic province related to the opening of the Central Atlantic and seems to be very similar to those founded in the Labrador Peninsula (Shelburne dyke) and in Morocco (Foum-Zguid dyke; Vegas, 2000). This large magmatic province suggests an Early Jurassic thermal anomaly at the base of the lithosphere within Pangea. An underplating process at the base of the crust can be deduced (De Boer, 1992). This vertical dolerite dyke crops out for more than 530 km with a variable width ranging from 5 to 200 m. Its composition is very homogeneous, typical of continental tholeiitic basalt. The absence of lava flows has been explained as a plume head detached with a quick cooling after impingement (Cebrià et al., 2003). This has affected the entire Iberian lithosphere.

The MP Fault nucleated on this dyke, but two different styles of deformation can be observed (ductile and brittle), both pointing to the left-lateral movement of the fault.

Arthaud and Matte (1975), in a paper that is probably one of the most cited studies on the tectonics of the Iberian Peninsula, dated this fault as Late Hercynian (Variscan). However, evidence that the fault had significant activity during the Cenozoic was long underestimated. Nevertheless, the presence of Cenozoic sediments in small basins along the fault trace were recognized early in Spain (Vegas, 1975), and the tectonic control along the SE margin of the Cenozoic Alvalade basin was recognized in Portugal (Cabral, 1995; Cunha et al., 2000; Pimentel, 1997, 1998). More recent studies found evidence of deformation in these sediments in the Spanish sector of the fault (de Vicente et al., 2004; Villamor, 2002).

From its NE termination at the Duero basin toward the SW, the MP Fault shows examples of brittle releasing and restraining steps from where a strike-slip left-lateral movement can be deduced (Figures 10 and 11). Several pull-apart basins are recognized, including the Plasencia, Moro, Cañaveral, and Rivera de Araya basins (Villamor, 2002; Figures 10 and 11). Crossing the Cabeza de Araya batholith, a series of alternating localized convergence and divergence zones along the MP Fault can be observed (Figure 10). According to Cunningham and Mann (2007), the Cañaveral basin (Figure 11) can be defined as an extensional duplex of three normal faults with the main subsiding area to the NE and, to the SW, a developed paired bend with a paired bend bypass fault to the south. Paleostress analysis close to Cañaveral (Figure 11) indicates an S_{hmax} almost parallel to the MP Fault.

Other small thrust-related basins appear at both sides of the fault (Amblés, Corneja, Cepeda, Zarza, and Coria; Figure 10), showing similar characteristics. They are limited by E-W thick-skinned thrusts that bend toward NW-SE close to the MP Fault. The thrusts in these basins typically appear offset by N-S (far from the MP Fault) to NE-SW left-lateral strike-slip faults (close to the MP Fault), with the same sense of displacement than the MP Fault (acting as transfer faults, not displacing the thrust segments). This tectonic arrangement indicates that N-S trending shortening bends toward NE-SW approaching the MP Fault.

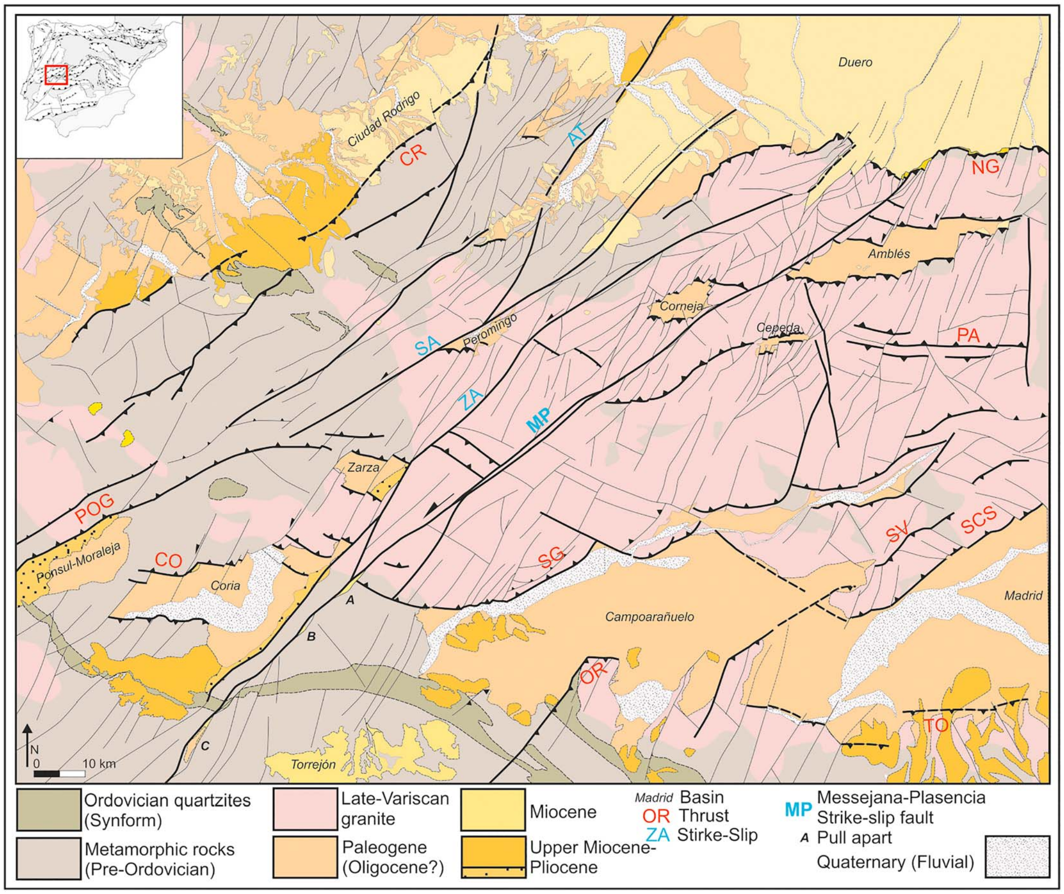

Figure 10. Geological map showing the Messejana-Plasencia fault in the area between Coria (SW) and Amblés (NE). Several pull-apart basins are shown. A (Plasencia), B (Moro), and C (Cañaveral pull-apart) also appears in Figures 11 and 12. Fault names are given in Figure 2. Names of the basins are also indicated.

The strike-slip displacement of the MP Fault ranges between 3 and 5 km (Villamor, 2002). In addition to this brittle displacement, a wide zone of ductile deformation can be observed affecting the entire Variscan structure (Figure 10). In this case the left-lateral offset can be up to several tens of kilometers. This ductile offset did not affect the Cabeza de Araya batholith (Figure 11), recently dated between 308 and 296 Ma (Rubio-Ordoñez et al., 2016. Consequently, if a late Variscan left-lateral shear zone existed, it had to be older than 308 Ma. With this in mind, it is difficult to assign a late Variscan age to the MP Fault.

In the Plasencia area (Figure 10), the elongated directional duplex contains a sedimentary infill that starts with a local red to orange gravelly (pebbles of slates) and silty lithostratigraphic unit (Barro Unit; Villamor, 2002). This unit has provided fossil remains of *Hispanotherium matritensis* (Hernández-Pacheco & Crusafont, 1960), typical of zone MN5 (middle Aragonian; Langhian, early Middle Miocene). This sedimentary record can be ascribed to the allostratigraphic unit UBS10.

The local Plasencia lithostratigraphic unit overlies, by sedimentary disconformity, the Barro unit and consists of a succession of heterometric gravels, with predominance of slate pebbles and interlayers of silty clays laterally discontinuous, indicating proximal and middle areas of alluvial fans. This sedimentary record can be ascribed to the UBS11. The Piñonate lithostratigraphic unit consists mainly of fine matrix-supported alluvial fan gravels, with rounded and small pebbles, which can be ascribed to the UBS12, overlain by the Fuentidueñas lithostratigraphic unit consisting of ochre massive coarse gravels outcropping in the SW of the local basin, which can be ascribed to the UBS13. All these three alostratigraphic units are gently dipping toward the MP fault (Villamor, 2002).

The unloading of the Alcántara dam in the Tagus River in 2009 allowed us to recognize the sedimentary infilling of the Cañaveral pull-apart basin (Figures 11 and 12). It starts with a unit of arkosic conglomerates

10.1029/2018TC005204

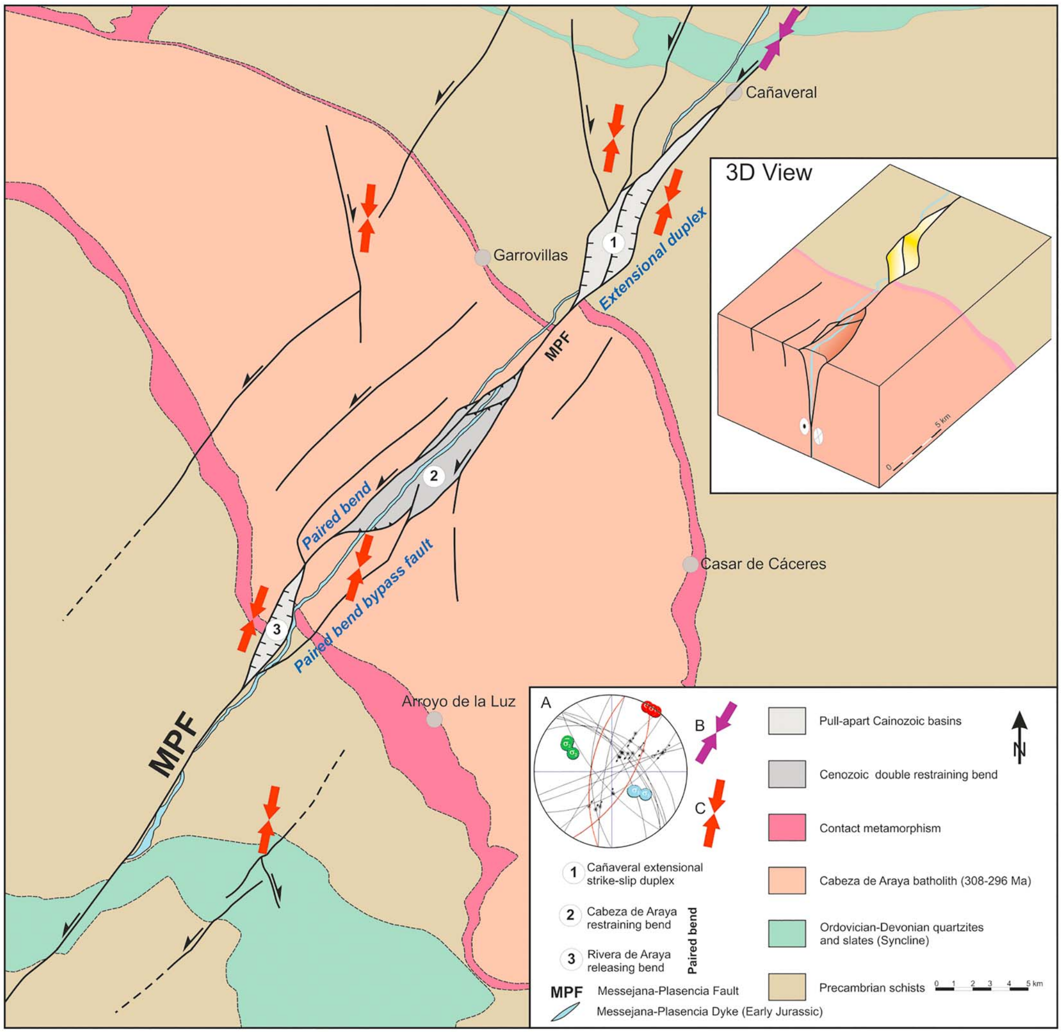

Figure 11. Detailed geological map and 3D sketch showing the Messejana-Plasencia fault arrangement in the area SW of Cañaveral. (1) Cañaveral extensional duplex. (2) Cabeza de Araya restraining bend. (3) Ribera de Araya pull-apart. (a) Paleostress data inversion from faults at the MP fault zone north of Cañaveral (red, σ_1; green, σ_2; blue, σ_3). The stress regime results in a mix of reverse and strike-slip faulting. S_{hmax} = purple arrows (b). (c) Maximum shortening direction deduced from conjugate strike-slip faults = red arrows.

fining upward into arkosic sandstones and feldspathic greywackes, ascribed to the Miocene (UBS9-10). Over this unit, forming a slight angular unconformity, a brown-colored unit comprises little red colored gravels and mudstones, with very poorly sorting (UBS11). This unit is overlaped, by disconformity, by a unit of red gravels and muds (UBS11). The culminant sedimentary unit of the basin consists of ochre poorly sorted very coarse gravels and sands (UBS13), also overlapping the previous unit.

In short, the sedimentary infilling in these two pull-apart basins shows similar characteristics as those from the main thrust-related basins. Arkosic conglomerates are found in the UBS9-10 (the source areas are granites), and UBS11, 12, and 13 have similar alluvial fan facies within the entire SPCS. Two main tectonic pulses can then be deduced, Pyrenean and Betics. The last deformation stage has taken place since the Upper Messinian-Lower Zanclean as the UBS12 is faulted in the Cañaveral extensional duplex (Figure 12).

5. Discussion

5.1. Pyrenean Strain Partitioning in the SPCS

Spatial differences in the Cenozoic structural style and deformation within the SPCS indicate a complex pattern of crustal scale strain partitioning (de Vicente, 2009). This process is observed on a wide range of

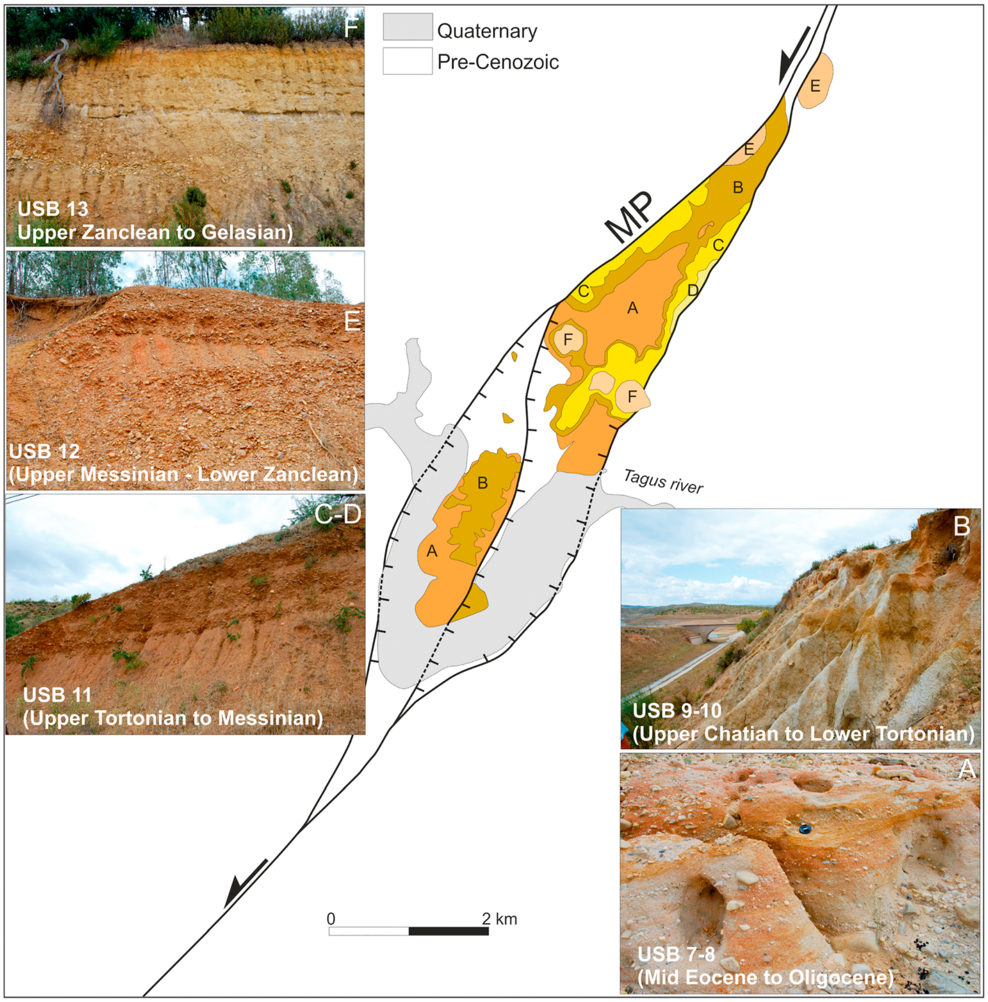

Figure 12. Typical exposures of the sedimentary record of the various tectonostratigraphic stages at the Cañaveral extensional duplex: (a) Lutetian to lower Chattian tectonostratigraphic stage (UBS7-8); (b) Upper Chattian to lower Tortonian tectonostratigraphic stage (UBS9-10); (c, d) Upper Tortonian to Messinian; (e) Upper Messinian to Lower Zanclean; (f) Upper Zanclean to Gelasian. MP = Messejana-Plasencia Fault.

scales spanning from the grain to lithospheric scale (Fitch, 1972; Lettis & Hanson, 1991; Molnar, 1992) but has not been well documented in an intraplate tectonic setting. Slip partitioning might represent a minimum energy condition (Michael, 1990), but one of the most important factors influencing the partition of the strain seems to be the preexistence of large structures that produce anisotropy in the deformed area (Jones & Tanner, 1995; Zoback et al., 1987).

The MP subvertical dyke, more than 500 km long and crossing the whole of the Iberian lithosphere, imposed a left-lateral strike-slip movement during the Pyrenean (N-S) related deformation. The related pull-apart geometries developed along the MP Fault indicate a pure strike-slip movement rather than transtension or transpression (Wu et al., 2009). To compensate such a movement, a series of parallel (NE-SW) thrusts were developed.

This structural arrangement can also be observed at outcrop scale along the MP Fault (Figure 13), displaying a positive flower structure with a pure strike-slip fault.

Other more complicated models to explain the intraplate tectonics of Iberia invoke large rotations of the direction of the maximum shortening direction during a relatively short time span (Liesa & Simón, 2007).

Regions with strain partitioning are often characterized by the presence of a high angle between the regional stress direction and the major faults trend (Zoback et al., 1987). This strong obliquity must be responsible for

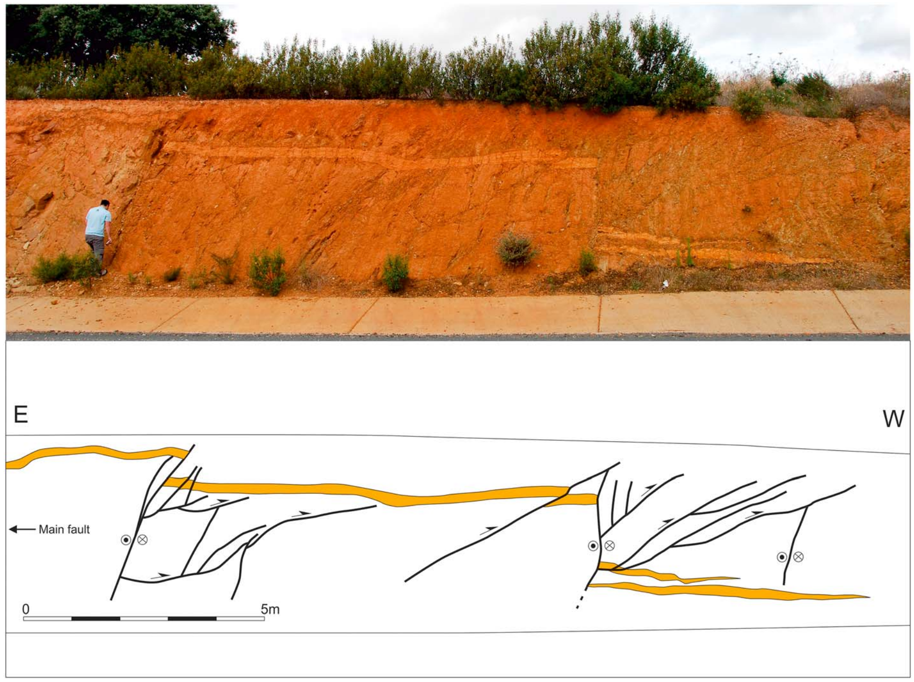

Figure 13. Photo and structural interpretation of positive flower structures related to pure strike-slip faults, with associated restraining bends. AP 66, Near Cañaveral.

both types (dip-slip and strike-slip movements) but not for defining the tectonic regime as transpressional (Audemard et al., 2005). The orientation of the MP Fault changes from N35E south of the SPCS to N57E toward its northeastern termination. It is especially in this northern area where strain partitioning is more obvious. The obliquity between the regional stress field and the orientation of the MP Fault appears to be a striking point in the development of the partitioned strain.

The parallelism between the SPCS and the Betics provided the argument to relate this range with compressive stresses transmitted from the south of Iberia, in the framework of a crustal detachment from the Betics (Ribeiro et al., 1990; Warburton & Alvarez, 1989). Nevertheless, the age of the most important deformation, deduced from the sedimentary infilling of the adjacent basins (Cunha, 1992a; de Vicente & Muñoz-Martín, 2012; Pais et al., 2012) and AFT data (De Bruijne & Andriessen, 2002), indicates a clear relation with the Pyrenean orogeny. The emplacement of the Alborán domain later reactivated the previous tectonic structures with a much smaller corresponding sediment volume. In the Portuguese sector of the SPCS, this late shortening seems to be more important than the one related with the first deformational stage (Cabral, 2012).

Paleostress analysis from fault slip data along the MP Fault shows an S_{hmax} almost parallel to the fault generating subsidiary NW-SE reverse faults, while along the main NE-SW thrusts sufficiently far from the strike-slip fault, a uniaxial shortening with perpendicular S_{hmax} to the NE-SW thrusts is recorded (Figure 14c). This situation results in the progressive bending of thrust traces toward the MP Fault, not as an effect of a left-lateral drag but by progressive shifting of the maximum shortening direction (Figures 11 and 14a).

The amount of shortening in partitioned thrusts and the horizontal displacement in the main strike-slip faults can be used to estimate the regional shortening trend in a similar way to that considered for slip vectors of interplate settings (McCaffrey et al., 2000). It is difficult to determine the total horizontal displacement in the strike-slip faults since some of them do not have clear markers for measurement. The same situation appears when evaluating the total shortening produced by the easternmost thrusts. Nevertheless, we can take the observed displacement in the MP Fault, 3–5 km (Villamor, 2002), and the shortening produced by the most important NE-SW thrusts (e.g., SCS), 5–9 km (de Vicente & Muñoz-Martín, 2012), as minimum values to

10.1029/2018TC005204

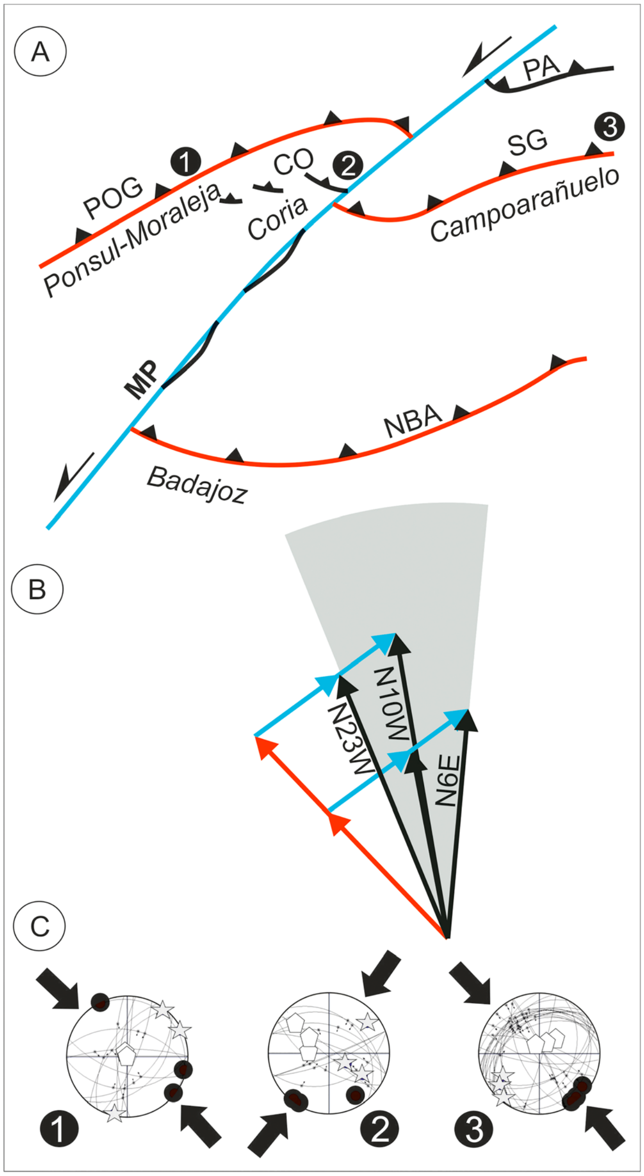

Figure 14. (a) Progressive bending of thrust traces toward the MP Fault by progressive shifting of the maximum shortening direction. Typical paleostress inversion results obtained far from the MP Fault (1) and (3) show a NW-SE S_{hmax} direction, whereas close to the fault, a NE-SW S_{hmax} is obtained. The results are plotted in C (black circles, σ_1; stars, σ_2; pentagons, σ_3). (b) The amount of shortening in partitioned thrusts, and the horizontal displacement in the main strike-slip faults, can be used to estimate the regional shortening.

calculate the resulting trend of the regional shortening. This results in a regional maximum shortening direction between N23W and N6E, with a most probable value of N10W, fitting well with the proposed Pyrenean origin of the strain partition (Figure 14b).

5.2. Deformational Models of the SPCS: Detachment Versus Lithospheric Folding

Recognition of the compressive origin of the Portuguese (Ribeiro, 1940, 1941) and the Spanish Central System (Birot & Solé-Sabarís, 1954) took place as early as the middle of the last century, before the establishment of the role that plate tectonics plays in the development of intraplate structures. However, these field observations were not taken into account, and for a long time, the SPCS was considered as an extensional structure with the development of raised horst and graben related to stationary continents (Alía, 1976). The first models, in an intraplate compressive context, began to appear in the late 1980s and early 1990s. Vegas and Suriñach (1987) calculated an intraplate crustal thickening of 5 km, while Warburton and Alvarez (1989) built a cross section with the development of thin-skinned tectonics related to an intracrust detachment from the Betics and with an associated shortening of 50 km. This idea was also proposed, although in less detail, by Ribeiro et al. (1990) for the Portuguese sector but related to a thick-skinned tectonic style and with a noticeably lesser amount of shortening. However, these studies lacked sufficient field observations. These were provided during the III Meeting (Field Trip) of the Tectonics Commission of the Spanish Geological Society (de Vicente & González-Casado, 1992). Then, the proposed tectonic style, which is the one considered today, was a thick-skinned tectonic arrangement with no detachments in the cover and the generation of imbricate thrusts systems and pop-ups within the Variscan basement. The related shortening was estimated at 14% (20 km). In view of these observations, the range structure proposed by Warburton and Alvarez (1989) has a number of inconsistencies (Figures 15 and 16).

Subsequently, the data provided by apatite fission track analysis, study of the sedimentary filling of the Madrid Basin, and gravimetric analysis made it possible to quantify the uplift, the depth of the range roots, and its age of deformation in the Spanish sector (de Vicente et al., 2007). The results were congruent with the idea that the Iberian microplate would have undergone an intense lithospheric folding process, whose most important structural expression was the SPCS (Cloetingh et al., 2002). In order to test this concept, both analogue and numerical modeling studies were carried out (Fernández-Lozano, 2012; Martín-Velázquez et al., 2009, Figure 17).

Recently, the idea of a crustal detachment has been taken up again considering two possibilities, namely, that the detachment comes from the Betics (south) or from the Pyrenees-Cantabrian Mountains (north; Quintana et al., 2015). These authors argue that it is not possible to have a local compensation by ductile thickening of the lithospheric mantle and the lower crust by means of a pure shear mechanism related to lithospheric folding. The main argument seems to be that the SPCS does not have deep crustal roots, and so, a simple shear detachment solution is preferred.

Nevertheless, the crustal models in the SPCS give a Moho depth ranging between 32 and 35 km, with up to 41 km in the NE sector (Figures 5 and 6a) where the cross section by Warburton and Alvarez was constructed (Figure 15). The surrounding areas show a Moho depth of 28–30 km. This provides an increase of 4.5 km in mean crustal thickness value (which could be larger than 14 km close to the Iberian Chain). Depending on

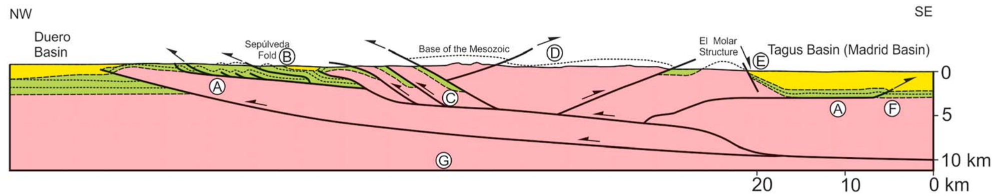

Figure 15. Structural inconsistencies, not supported by field observations, of the Warburton and Alvarez (1989) cross section, represented in the figure. (A) Cretaceous sediments do not appear to be detached from the basement. The sandstones of the Utrillas Fm. (base of the Cretaceous) do not constitute, at any point in Iberia, a detachment level for the Alpine deformation. (B) The Sepúlveda fold is not a thin-skinned structure as at its core the Variscan basement outcrops (Figure 16). (C) In the frontal part of Somosierra, the lateral relations that appear in the geological cartography do not support the concept of Cretaceous sediments sheltered under the basement thrusts with the indicated displacement. (D) The base of the Mesozoic, eroded above the basement, is not constrained by any data leaving its position as arbitrary. (E) The S border of the Central System is a thrust that accumulates more than 5 km of vertical throw, as evidenced by existing seismic lines (de Vicente & Muñoz-Martín, 2012). In any case is it a normal fault. (F) The geometry of the basement top in the Madrid basin is very flat and without observed additional evidence for Cretaceous folds detached from the Utrillas Fm (de Vicente & Muñoz-Martín, 2012). (G) The cross section does not provide any data on the Moho depth.

the thermal age, the rheology of the crust and of the lithospheric mantle, the resulting folding wavelength and thus the resulting Moho depths can vary widely. Moreover, different styles of lithospheric folding have been defined: linear, irregular, or intermediate (Cloetingh et al., 1999). Undulations ranging between 4 and 5 km of the mantle-crust limit are found in the irregular lithospheric folding of the Pannonian Basin. Thus, to evaluate this large-scale tectonic process, a large-scale analysis must be completed and not only the study of a single fold. For the Iberian microplate, this type of analysis was performed, even for its oceanic crustal part (Muñoz-Martín et al., 2010), leading to the conclusion that lithospheric folding affected the entire Iberian microplate and not only the SPCS.

The integrated length of the Pyrenees, Cantabrian Mountains, and, probably, the Galicia Bank is similar to that of the Iberian Chain, the SPCS (Spanish and Portuguese sectors), the Western Mesozoic Terrains, and the offshore Extremadura Spur (the latter already in transitional continental-oceanic crust). This similar length and parallelism supports the idea of lithospheric folding. In this context, the occurrence of the left-lateral strike-slip faults of MVB and PRV, which transferred the deformation from the Cantabrian Mountains toward the SPSC (Heredia et al., 2004; Vegas et al., 2004), would cut the detachment proposed by Quintana et al. (2015).

Considering the relative situations of the Alborán Domain and the Portuguese sector of the SPCS, the proposed detachment cannot explain the location of the entire SPCS.

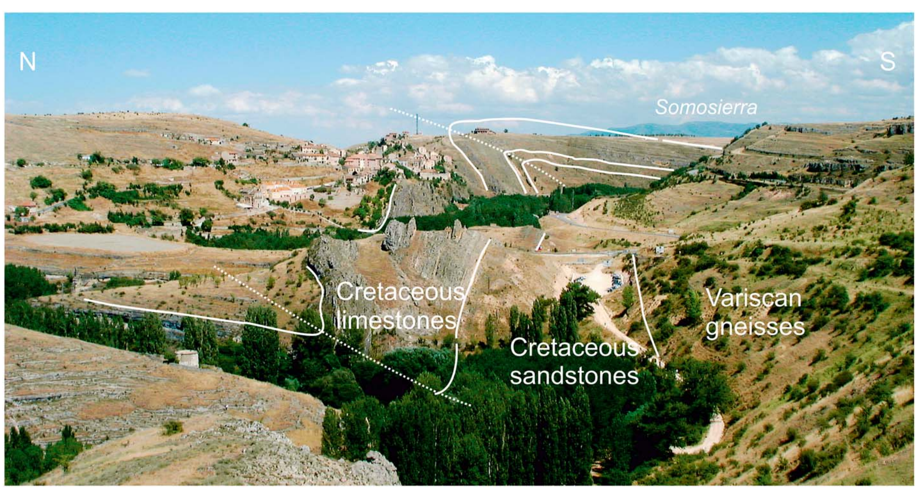

Figure 16. The Sepulveda fold to the north of Somosierra in the Honrubia Massif. In the core, there are Variscan gneisses. There is no duplication of the Cretaceous series by a thin-skinned thrust (Figure 15b).

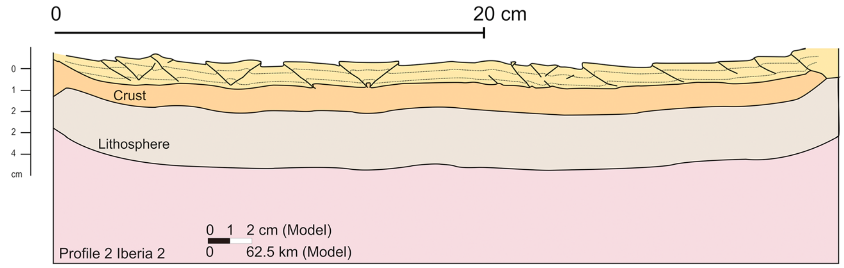

Figure 17. Example of a scaled analogue model for the development of lithospheric folds in the Iberian microplate with the formation of cortical pop-ups similar to the SPCS (Fernández-Lozano, 2012).

Finally, the cortical transect contructed by these authors through Iberia has several incongruencies: it begins to the north in the Basque-Cantabrian sector (in front of the Iberian Chain and not in front of the SPCS) instead of beginning in the Cantabrian Mountain Range, which is where the detachment is supposed to be rooted. They also make an extensive use of the Warburton and Alvarez cross section, which as mentioned above is inconsistent. They do not use the most recent data on the crustal structure of Iberia provided by the TOPOIBERIA project (Díaz & Gallart, 2009). Also in the scope of this project, a deep magnetotelluric (MT) profile was carried out crossing the Gredos area (Figure 6b; Pous et al., 2012). Taking into account that such a detachment should be a fluid migration surface area, it should appear in the magnetotelluric profile. Moderately dipping thrust faults are clearly marked, but no detachment occurs. Taking into account all these considerations, it appears that the concept of an intracrustal detachment connecting the SPCS and the Betics or Pyrenees (Cantabrian Mountains) does not hold up. Instead, the central deformation belt of Iberia (Iberian Chain, Central System, Portuguese and Spanish sectors, and the Extremadura Spur) appears to be the result of a process of lithospheric folding affecting the entire microplate.

An intermediate geometry was proposed by Casas and Faccenna (2000). These authors suppose a continuous deformation of the Iberian lithosphere as a result of in-plane compression caused by the slow advancing Nubia plate that reactivated previous (Eocene-Early Oligocene) Pyrenean structures. A generalized increase of the intraplate stresses during the Late Eocene-Early Miocene should be produced by the consumption of the Tethyan ocean and the beginning of the collisional process in the Betics. This should have resulted in the locking of subduction and beginning of collision in the Iberia-Nubia boundary with the formation of a detachment at the base of the crust. From this perspective, Iberia should represent an example of transition from the localized (subduction) to delocalized (lithospheric-crustal folding over the entire peninsula) style of deformation. To produce lithospheric folding, the involved plates must be mechanically coupled. The origin of such a coupling could be as follows: (1) Iberia was part of Nubia when lithospheric folding was developed, and then the Alborán Domain (subduction) decoupled Iberia from Nubia; or (2) collisional processes related to the Alborán Domain acted as a coupled border for a short period of time. In any case, the final result was a distributed folding and buckling over the entire peninsula.

Studies from long continuous GPS position time series studying vertical deformation rates along the Nubia-Eurasia plate boundary (Serpelloni et al., 2013) support the concept of lithospheric folding with wavelengths of a few hundred kilometers. This study indicates that the SPCS is uplifting by up to 1 mm/year, and the Duero basin is subsiding close to −3 mm/year. Thus, the origin of Iberian topography and undulations could be related to lithospheric folding, causing the differential uplift of different parts of the Iberian plate and controlling the distribution of basins and mountain chains, bounded by folds and faults (Serpelloni et al., 2013).

5.3. Tectonic Evolution

The strain partitioning model, the sedimentary infilling of the coeval tectonic basins, and AFT data support the idea of only two main deformational events in the SPCS during the Cenozoic. A Pyrenean N-S trending paleostress field could have started at the beginning of UBS7 (Lutetian), even though in the eastern sector it was probably recorded earlier with an NNE-SSW S_{hmax} (Figure 8). The unconformity between UBS7 and UBS8 must be attributed to the westward propagation of the Pyrenean hinterland toward the Cantabrian Mountains, where the main registered uplift was at the Eocene-Oligocene transition. Then, the S_{hmax}

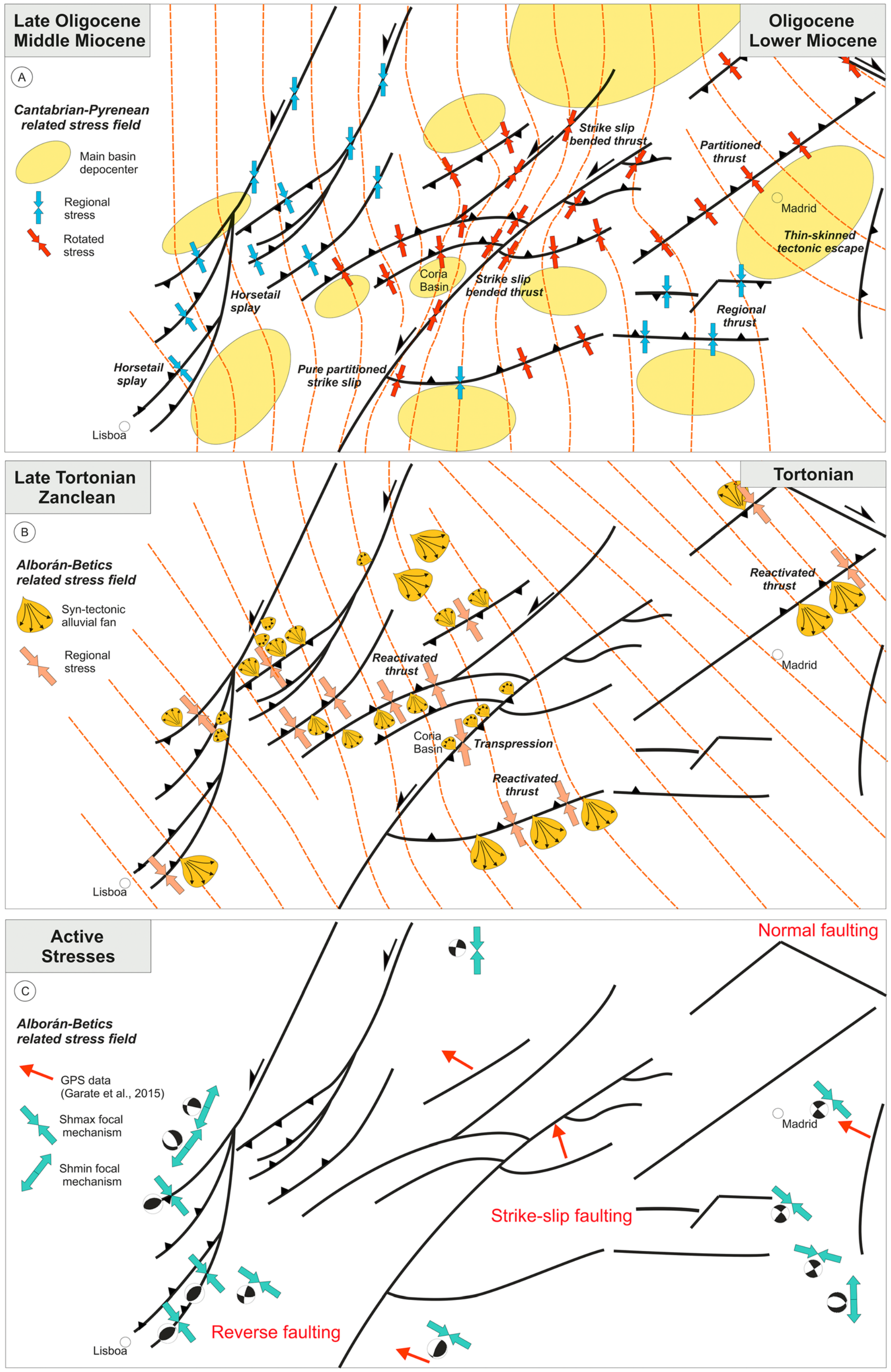

Figure 18. Phases of tectonic evolution of central-western Iberia during the Cenozoic. (a) Main (Pyrenean) structuration. N-S regional shortening with strain partitioning. (b) Betic NW-SE rejuvenation. (c) Active stresses. Major faults are drawn. Same area as displayed in Figures 2, 4, and 5. Delay times between Eastern and Western zones are also labeled. GPS data from Garate et al. (2015).

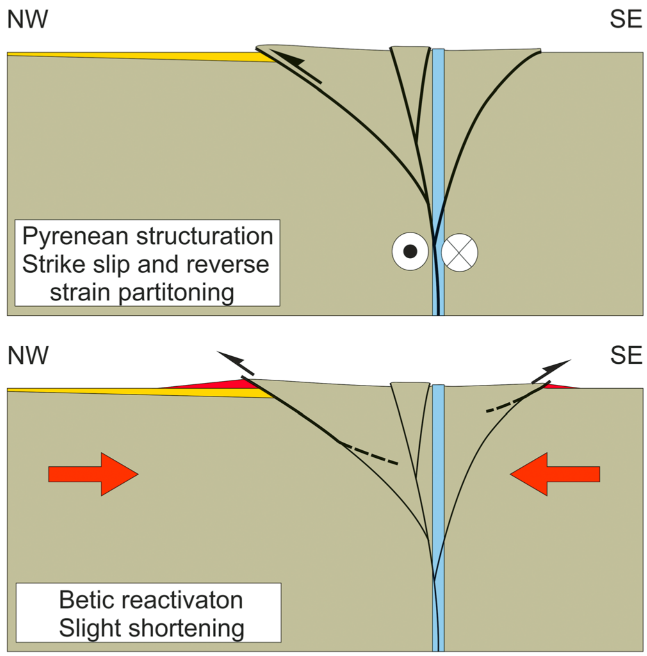

Figure 19. Reactivation of Pyrenean positive flower structures as thrusts during the Betic rejuvenation.

turned to N-S, generating the intraplate deformation climax during the transition between UBS8 and UBS9, which was registered in all the surrounding basins with the noticeable increase of prograding alluvial fans and conglomerates as well as progressive and angular unconformities. Nevertheless, the maximum tectonic climax registered in the westernmost sector of the SPCS occurred later (Upper Miocene), evidencing its diachronic nature. If no strain partitioning occurred, we would require three different tectonic events at least: NE-SW compression to be able to move the MP fault as a pure left-lateral strike-slip fault, a NW-SE shortening related to the NE-SW thrusts, and a N-S shortening related to the E-W thrusts. Since a single N-S S_{hmax} with strain partitioning can explain all the regional deformation and related stresses, it appears that this is the most accurate solution. Taking all these arguments into account, the Pyrenean intraplate stress field should have large deflections close to the MP fault (Figure 18a) as evidenced by the thrust bends close to it. Out of the MP fault influence, the PRV and MVB left-lateral deformation belts and their related horsetail splays, as well as the Toledo Mountains, were developed as a single, not partitioned, N-S shortening. Pull-apart basins along the MP fault should have developed simultaneously with the main SPCS thrusts as evidenced by the coeval sedimentary infilling. The overall tectonic arrangement along the MP fault is of a positive flower structure showing parallel faults with a clear reverse component and a pure strike-slip fault in the middle.

During the next (Betic, NW-SE) compressional stage, some of these faults (almost perpendicular to the renewed stress field) resulted in thrust reactivation, especially along the eastern border of the Coria basin (Figures 18b, 18c, and 19), although some transpressional deformation cannot be excluded (Figure 10). During this event, fault displacements were smaller than in the previous stage, as were the related volumes of sediments. Nevertheless, as it was a recent event (which we can consider as neotectonics), its geomorphological expression is much more noticeable (e.g., Guadalupe and Estrela), especially in the Portuguese sector where the main tectonic event is then reached. The PRV and MVB faults again registered a renewed left-lateral movement and are considered as active faults (Cabral, 1995, 2012). Thus, some northward bending of the Betic stress field can be deduced to the NW of the SPCS. The first influence of the Betics compression toward its foreland could have started during the Late Burdigalian, being responsible for the slight unconformity between UBS9 and UBS10 and the recorded uplift in the SPCS (De Bruijne & Andriessen, 2002). Then, the regional stress field started to rotate toward NW-SE (Figure 8). Nevertheless, the main Betics-related paleostress field occurred at the base of UBS11 during the Tortonian, clearly NW-SE oriented. The erosional process of the Madrid basin started before the sedimentation of the UBS11-13 alluvial fans (de Vicente & Muñoz-Martín, 2012). As a result, the endorheism of the Duero and Madrid basins ended, with a general tilting of Iberia toward the west and the opening to the Atlantic, resulting in a general geomorphological rearrangement.

The Pyrenean and Betics stress fields must have experienced some time delay between the eastern and western sectors of the SPCS since both of them initially started in Eastern Iberia. In fact, in the eastern sector the main deformational pulses took place during the Oligocene-Early Miocene and during the Tortonian, whereas in the western sector, they were recorded during the Late Oligocene and Late Tortonian-Zanclean time spans (Figures 18a and 18b).

This kind of difference between the eastern and the western parts of the SPCS is also evident nowadays. Active stresses are compressional leading to reverse faulting in the Portuguese area, whereas close to the Iberian Chain, strike-slip to normal faulting prevails (de Vicente et al., 2008; Figure 18c). Presently, a slight bend toward the WNW-ESE of S_{hmax} seems to occur in the SW of Iberia (Cabral et al., 2017; Cabral & Ribeiro, 1988; Ribeiro et al., 1996).

Near the surface, some of the Pyrenean positive flower structures were reactivated as pure reverse faults during the Betic event (Figure 19), as evidenced by thick-skinned thrusts with some tens of meters of throw affecting UBS11-12 (Figure 9c)

6. Conclusions

During the Cenozoic intraplate deformation of Iberia, an intense and distributed deformation was recorded. The related most important tectonic feature is a central deformation belt crossing the Peninsula from the Mediterranean to the Atlantic. It comprises two different ranges: The Iberian Chain and the SPCS sharing a similar tectonic evolution related to the transmission of compressive stresses from two closely located orogens, the Pyrenees and the Betics. Nevertheless, the structural style is quite different, since the SPCS is not a previous sedimentary basin inverted during these compressional stages. This supports the concept of lithospheric folding affecting the Iberian microcontinent.

Intraplate ranges of Iberia show a wide variety of structural trends. In early studies, this assortment was related to distinct tectonic phases—there are up to five that explain every individual range and its related paleostresses, taking place at different time spans. However, the sedimentary record and AFT data indicate that the main deformational period took place at the same time in most of them, related to the Pyrenean orogen except in the western Portuguese sector, where the peak of the Cenozoic deformation was reached later (Betic tectonic phase). Tranpressional deformation, escape tectonics, and strain partitioning can also produce the apparently complex tectonic structuration. Therefore, the Betic intraplate compression was only able to rework previous structures during a short period of time (ca. 9–3.7 Ma).

The SPCS is a thick-skinned crustal pop-up, 2500 m high, 700 km long, evidencing 5 km of throw in the SCS thrust. It separates the Duero Cenozoic basin to the north from the Madrid-Lower Tagus basins to the south. Thrust orientation varies from NE-SW to E-W with double vergence, although main displacements are located to the south. Minor pop-ups, triangle zones, and imbricate thrusts developed along the range, producing small intramountain basins filled with Cenozoic sediments. The SPCS terminates against the Iberian Chain to the east in a crustal transpressive right-lateral tear deformation belt.

Crossing the SPCS crustal pop-up, the MP left-lateral strike-slip fault was nucleated on an Early Jurassic dolerite dyke showing a horizontal displacement of 3 to 5 km. Several releasing and restraining bends are conspicuous along the fault, with pull-apart basins filled by Cenozoic sediments. Its general tectonic arrangement draws a positive flower-like structure, probably retightened during the last deformation event (Betic). It is noticeable that the fault is not well oriented to move as a strike-slip fault, especially when crossing the SPCS, neither for the Pyrenean nor for the Betic intraplate compressive stresses.

Available data on the crustal structure below the SPCS indicates the presence of a cortical thickening with Moho depths of 33 to 36 km that correlates well with the location of the main thrusts. There are some local data indicating a Moho depth of up to 41 km. The unthickened regional Moho level is located at around 28 km depth. This crustal pattern is thus related to the Cenozoic intraplate deformation and not to the Variscan structuration. Along the MP, MVB, and PRV strike-slip faults, an elongated relative minimum of the Moho depth is also observed.

The stratigraphic record of the main endorheic basins, but also of the intramountain thrust-related basins and pull-apart basins along the strike-slip faults, has a very similar infilling history. The beginning of the N-S (Pyrenean) compression is registered during the UBS6 sedimentation, but the maximum compression is recorded during the upper Priabonian to lower Chattian (UBS8), except in the Portuguese sector (UBS10). The upper Tortonian to present tectonostratigraphic stage records the maximum of the Betic intraplate deformation, especially during the sedimentation of UBS11 and UBS12. USB13 signals the beginning of the Atlantic exorheism in all the basins.

Thrust bending toward the MP Fault clearly indicates a common tectonic process being able to produce both types of faults at the same time. Strain partitioning between the MP strike-slip fault and the main NE-SW-oriented thrusts results in an overall shortening trend ranging between N23W and N6E, with a most probable value of N10W that fits well with the Pyrenean origin of the SPCS. Therefore, the presence of the MP vertical dyke could have imposed the process of strain partition, and consequently, NE-SW thrusts were developed.

No evidence exists for an intracortical detachment connecting the SPCS with the Pyrenean or the Betics Orogens. The range must therefore be an expression of lithospheric folding affecting the entire Iberian paleo-microplate.

Acknowledgments

Some of the original data sets used in this study were obtained during the TOPOIBERIA project, mainly based on data published by Díaz and Gallart (2009). Project data are accessible via http://www.igme.es/TopoIberia/default.html or http://www.ictja.csic.es/index.php/research/projects/public-funding-past-projects/412topoiberia?jjj=1538644040561. Geological maps from Spain, Istituto Geológico y Minero de España, (IGME) are accessible via http://info.igme.es/cartografiadigital/geologica/Magna50.aspx and from Portugal, LNEG, via http://www.lneg.pt/servicos/139/1239. This study was supported by the Consolider Ingenio 2006 "TOPOIBERIA" CSD2006-00041, the Spanish National Research Programme CGL2006-13926-C02-01-02 "Topoiberia Foreland," and projects by the Fundação para a Ciência e a Tecnologia through UID/MAR/04292/2013 (MARE). The authors wish to thank Luis Matias, Ana Machadinho, and Fernando Lopes for access to geophysical data. The authors thank Antonio Casas-Sainz and João Cabral for constructive and insightful reviews.

References

Alía, M. (1976). Una Megaestructura de la Meseta Ibérica: la Bóveda Castellano-Extremeña. *Estudios Geológicos*, *32*, 229–238.

Andriessen, P. A. M., & Zeck, H. P. (1996). Fission-tracks constrains on timing of Alpine nappe emplacement and rates of cooling and exhumation, Torrox area, Betic Cordilleras, S. Spain. *Chemical Geology*, *131*(1-4), 199–206. https://doi.org/10.1016/0009-2541(95)00148-4

Antunes, M. T., Elderfield, H., Legoinha, P., & Pais, J. (1995). Datações isotópicas com Sr do Miocénico do flanco sul da Serra da Arrábida. *Comun. Inst. Geol e Min.*, *81*, 73–78.

Arthaud, F., & Matte, P. (1975). Les decrochements tardi-hercyniens du sud-ouest de l´europe. Geometrie et essai de reconstitution des conditions de la deformation. *Tectonophysics*, *25*(1), 139–171. https://doi.org/10.1016/0040-1951(75)90014-1

Audemard, F. A., Romero, G., Rendon, H., & Cano, V. (2005). Quaternary fault kinematics and stress tensors along the southern Caribbean from fault-slip data and focal mechanism solutions. *Earth-Science Reviews*, *69*, 181–233. https://doi.org/10.1016/j.earscirev.2004.08.001

Birot, P. & Solé-Sabarís, L. (1954). Investigaciones sobre morfología de la Cordillera Central Española. *C.S.LC. Madrid*. 87.

Cabral, J. (1995). Neotectónica em Portugal Continental. *Memórias do Instituto Geológico e Mineiro*, *31*, 265.

Cabral, J. (2012). Neotectonics of mainland Portugal: State of the art and future perspectives. *Journal of Iberian Geology*, *38*(1), 71–84. https://doi.org/10.5209/rev_JIGE.2012.v38.n1.39206

Cabral, J., Mendes, V. B., Figueiredo, P., Brum da Silveira, A., Pagarete, J., Ribeiro, A., et al. (2017). Active tectonics in Southern Portugal (SW Iberia) inferred from GPS data. Implications on the regional geodynamics. *Journal of Geodynamics*, *112*, 1–11. https://doi.org/10.1016/j.jog.2017.10.002

Cabral, J., & Ribeiro, A. (1988). Carta Neotectónica de Portugal na escala 1/1000000. *Serviços Geológicos de Portugal*.

Calvo, J., Daams, R., Morales, J., Lopez-Martínez, N., Agusti, J., Anadon, P., et al. (1993). Up-to-date Spanish continental Neogene synthesis and paleoclimatic interpretation. *Revista de la Sociedad Geológica de España*, *6*(3–4), 29–40.

Calvo, J. P. (2004). Rasgos comunes de las Cuencas cenozoicas. In J. A. Vera (Ed.), *Geología de España, Sociedad Geológica de España*, (pp. 584–586). Madrid: Instituto Geológico y Minero de España.

Casas, A. M., & Faccenna, C. (2000). Tertiary compressional deformation of the Iberian plate. *Terra Nova*, *13*, 281–288.

Cebrià, J. M., López-Ruiz, J., Doblas, M., & Munha, L. (2003). Geochemistry of the Early Jurassic Messejana-Plasencia dyke (Portugal-Spain): Implications on the origin of the Central Atlantic magmatic province. *Journal of Petrology*, *44*(3), 547–568. https://doi.org/10.1093/petrology/44.3.547

Cloetingh, S., Burov, E., Beekman, F., Andeweg, B., Adriessen, P. A. M., García-Castellanos, D., et al. (2002). Lithospheric folding in Iberia. *Tectonics*, *21*(5), 1041. https://doi.org/10.1029/2001TC901031

Cloetingh, S., Burov, E., & Poliakov, A. (1999). Lithosphere folding: Primary response to compression? (from central Asia to Paris Basin). *Tectonics*, *18*, 1064–1083.

Comas, M. C., Platt, J. P., Soto, J. I., & Watts, A. B. (1999). The origin and tectonic history of the Alboran Basin: Insights from Leg 161 results. In Z. Zahn, M. C. Comas, & A. Klaus (Eds.), *Proceedings ODP, Scientific Results*, (pp. 555–580). College Station, TX: Ocean Drilling Program.

Cunha, P. P. (1992a). Estratigrafia e sedimentologia dos depósitos do Cretácico Superior e Terciário de Portugal Central, a leste de Coimbra. Ph.D. Thesis, Univ. Coimbra, 262 pp.

Cunha, P. P. (1992b). Establishment of unconformity-bounded sequences in the Cenozoic record of the western Iberian margin and synthesis of the tectonic and sedimentary evolution in central Portugal during Neogene. *First Congress R.C.A.N.S. - "Atlantic general events during Neogene" (Abstracts Book)*, Lisboa, (pp. 33-35).

Cunha, P.P. (2008). Papel desempeñado por la tectónica, el clima y el eustatismo en la génesis de los depósitos de Raña al pie de la Cordillera Central Portuguesa (Iberia occidental). Actas del VII Congreso Geológico de España, La Palma de Gran Canária, *Geo*-Temas (ISSN: 1567-5172), 10, 1507-1510.

Cunha, P. P., Barbosa, B. P., & Reis, R. P. (1993). Synthesis of the Piacenzian onshore record, between the Aveiro and Setúbal parallels (Western Portuguese margin). *Ciências da Terra*, *12*, 35–43.

Cunha, P. P., Martins, A. A., Huot, S., Murray, A., & Raposo, L. (2008). Dating the Tejo River lower terraces in the Ródão area (Portugal) to assess the role of tectonics and uplift. *Geomorphology*, *102*, 43–54. http://hdl.handle.net/10316/15177

Cunha, P. P., Pimentel, N. L., & Pereira, D. I. (2000). Assinatura tectono-sedimentar do auge da compressão bética em Portugal, A descontinuidade Valesiano terminal-Turoliano. *Ciências da Terra*, *14*, 61–72.

Cunningham, W. D., & Mann, P. (2007). Tectonics of strike-slip restraining and releasing bends. *Geological Society, London, Special Publications*, *290*, 1–12. https://doi.org/10.1144/SP290.1

Curtis, M. L. (1999). Structural and kinematic evolution of a Miocene to Recent sinistral restraining bend: the Montejunto massif, Portugal. *Journal of Structural Geology*, *21*, 39–54. https://doi.org/10.1016/S0191-8141(98)00095-9

De Boer, J. Z. (1992). Eastern North American Mesozoic magmatism. *Geological Society of America Special Paper*, *268*, 361–378. https://trove.nla.gov.au/version/43100635

De Bruijne, C. H., & Andriessen, P. A. M. (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. https://doi.org/10.1016/S0040-1951(02)

de Vicente, G. (2009). Partición de la deformación Cenozoica intraplaca en el Sistema Central. *Geogaceta*, *46*, 23–26.

de Vicente, G., Cloetingh, S., Muñoz-Martín, A., Olaiz, A., Stich, D., Vegas, R., et al. (2008). Inversion of moment tensor focal mechanisms for active stresses around Microcontinent Iberia: Tectonic implications. *Tectonics*, *27*, TC1009. https://doi.org/10.1029/2006TC002093

de Vicente, G., Cloetingh, S., Van Wees, J. D., & Cunha, P. P. (2011). Tectonic classification of Cenozoic Iberian foreland basins. *Tectonophysics*, *502*(1–2), 38–61. https://doi.org/10.1016/j.tecto.2011.02.007

de Vicente, G., Giner, J. L., Muñoz-Martín, A., González-Casado, J. M., & Lindo, R. (1996). Determination of present-day stress tensor and neotectonic interval in the Spanish Central System and Madrid Basin, central Spain. *Tectonophysics*, *266*, 405–424. https://doi.org/10.1016/S0040-1951(96)00200-4

de Vicente, G. & González-Casado, J. M. (1992). Las deformaciones alpinas en el Sistema Central Español. *III Reunión de la Comisión de Tectónica de la Sociedad Geológica de España. Field Guide*, 150 pp.

de Vicente, G., & Muñoz-Martín, A. (2012). The Madrid Basin and the Central System: A tectonostratigraphic analysis from 2D seismic lines. *Tectonophysics*, *602*, 259–285. https://doi.org/10.1016/j.tecto.2012.04.003

de Vicente, G., & Vegas, R. (2009). Large-scale distributed deformation-controlled topography along the western Africa–Eurasia limit: Tectonic constraints. *Tectonophysics*, *474*, 124–143. https://doi.org/10.1016/j.tecto.2008.11.026

de Vicente, G., Vegas, R., Martín, A. M., Silva, P. G., Andriessen, P., Cloetingh, S. A. P. L., & Olaiz, A. (2007). Cenozoic thick-skinned deformation and topography evolution of the Spanish Central System. *Global and Planetary Change*, *58*(1-4), 335–381. https://doi.org/10.1016/j.gloplacha.2006.11.042

de Vicente, G., Vegas, R., Muñoz-Martín, A., González-Casado, J. M., Carbó, A., Alvarez, J., Cloetingh, S., et al. (2004). In A. Vera (Ed.), *El Sistema Central, Geología de España*, (pp. 621–626). Madrid: SGE-IGME.

de Vicente, G., Vegas, R., Muñoz-Martín, A., Van Wees, J. D., Casas-Sainz, A., Sopeña, A., & Fernández-Lozano, J. (2009). Oblique strain partitioning and transpression on an inverted rift: The Castilian Branch of the Iberian Chain. *Tectonophysics*, *470*(3), 224–242. https://doi.org/10.1016/j.tecto.2008.11.003

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 pp.

Dewey, J. F., Helman, M. L., Turco, E., Hutton, D. H. W., & Knott, S. D. (1989). Kinematics of the Western Mediterranean. In M. P. Coward, D. Dietrich, & R. G. Park (Eds.), *Alpine tectonics*, *Geological Society Special Publication*, (Vol. 45, pp. 265–283). London: Geological Society.

Díaz, J., & Gallart, J. (2009). Crustal structure beneath the Iberian Peninsula and surrounding waters: A new compilation of deep seismic sounding results. *Physics of the Earth and Planetary Interiors*, *173*, 181–190. https://doi.org/10.1016/j.pepi.2008.11.008

Diaz, J., Gallart, J., & Carbonell, R. (2016). Moho topography beneath the Iberian-Western Mediterranean region mapped from controlled-source and natural seismicity surveys. *Tectonophysics*, *692*, 74–85. https://doi.org/10.1016/j.tecto.2016.08.023

Dündar, S., Dias, N. A., Silveira, G., Kind, R., Vinnik, L., Matías, L., & Biancho, M. (2016). Estimation of the crustal bulk properties beneath mainland Portugal from *P*-wave teleseismic receiver functions. *Pure and Applied Geophysics*, *173*, 1949–1970. https://doi.org/10.1007/s00024-016-1257-4

Dunn, A. M., Reynolds, P. H., Clarke, D. B., & Ugidos, J. M. (1998). A comparison of the age and composition of the Shelburne dyke, Nova Scotia, and the Messejana dyke, Spain. *Canadian Journal of Earth Sciences*, *35*, 1110–1115. https://doi.org/10.1139/e98-058

Fernández-Lozano, J. (2012). Cainozoic deformation of Iberia: A model for intra-plate mountain building and basin development based on analogue modelling. *PhD Thesis. Utrecht University*. 250pp.

Fernández-Lozano, J., Sokoutis, D., Willingshofer, E., Cloetingh, S. P. A. L., & de Vicente, G. (2011). Cenozoic deformation of Iberia: A model for intraplate mountain building and basin development based on analogue modelling. *Tectonics*, *30*, TC1001. https://doi.org/10.1029/2010TC002719

Fillon, C., Pedreira, D., van der Beek, P. A., Huismans, R. S., Barbero, L., & Pulgar, J. A. (2016). Alpine exhumation of the central Cantabrian Mountains, Northwest Spain. *Tectonics*, *35*, 339–356. https://doi.org/10.1002/2015TC004050

Fitch, T. J. (1972). Plate convergence, transcurrent faulting and internal deformation adjacent to Southeast Asia and Western Pacific. *Journal of Geophysical Research*, *77*, 4432–4460.

Garate, J., Martín-Davila, J., Khazaradze, A., Echeverría, A., Asensio, E., Gil, A. J., de Lacy, M. C., et al. (2015). Topo-Iberia project: CGPS crustal velocity field in the Iberian Peninsula and Morocco. *GPS Solutions*, *19*, 287–295. https://doi.org/10.1007/s10291-014-0387-3

Heredia, N., Rodríguez-Fernández, L. R., Vegas, R., de Vicente, G., Cloetingh, S. P. A. L., Giner, J., & González-Casado, J. M. (2004). Cadenas cenozoicas del Noroeste Peninsular. In A. Vera (Ed.), *Geología de España*, (pp. 619–621). Madrid: SGE-IGME.

Hernández-Pacheco, F., & Crusafont, M. (1960). Primera caracterización paleontológica del Terciario de Extremadura. *Bol. Real Soc. Esp. Hist. Nat. Sec. Geológica*, *63*, 275–282.

Jones, R. R., & Tanner, P. W. G. (1995). Strain partitioning in transpression zones. *Journal of Structural Geology*, *17*, 793–802. https://doi.org/10.1016/0191-8141(94)00102-6

Kullberg, M. C., Kullberg, J. C., & Terrinha, P. (2000). Tectónica da Cadeia da Arrábida. In Tectónica das regiões de Sintra e Arrábida. *Mem. Geociências. Univ. Lisboa*, *2*, 35–84.

Laske, G., Masters, G., Ma, Z., & Pasyanos, M. (2013). Update on CRUST1. 0—A 1-degree global model of Earth's crust. *Geophysical Research Abstracts*, *15*, 2658.

Lettis, W. R., & Hanson, K. L. (1991). Crustal strain partitioning: Implications for seismic hazard assessment in western California. *Geology*, *19*(6), 559–562. https://doi.org/10.1130/0091-7613(1991)019<0559:CSPIFS>2.3.CO;2

Liesa, C. L., & Simón, J. L. (2007). A probabilistic approach for identifying independent remote compressions in an intraplate region: The Iberian Chain (Spain). *Mathematical Geology*, *39*, 337–348. https://doi.org/10.1007/s11004-007-9084-x

Mancilla, F. D. L., & Diaz, J. (2015). High resolution Moho topography map beneath Iberia and Northern Morocco from receiver function analysis. *Tectonophysics*, *663*, 203–211. https://doi.org/10.1016/j.tecto.2015.06.017

Mancilla, F. D. L., Stich, D., Morales, J., Martín, R., Diaz, J., Pazos, A., & Gonzalez-Lodeiro, F. (2015). Crustal thickness and images of the lithospheric discontinuities in the Gibraltar arc and surrounding areas. *Geophysical Supplements to the Monthly Notices of the Royal Astronomical Society*, *203*(3), 1804–1820.

Martín-Velázquez, S., de Vicente, G., & Elorza, F. J. (2009). Intraplate stress state from finite element modelling: The southern border of the Spanish Central System. *Tectonophysics*, *473*, 417–427. https://doi.org/10.1016/j.tecto.2009.03.024

McCaffrey, R., Zwick, P. C., Bock, Y., Prawirodirdjo, L., Genrich, J. F., Stevens, C. W., Puntodewo, S. S. O., et al. (2000). Strain partitioning during oblique convergence in northern Sumatra: Geodetic and seismologic constrains and numerical modelling. *Journal of Geophysical Research*, *105*(B12), 363–376. https://doi.org/10.1029/1999jb900362

Michael, A. J. (1990). Energy constraints on kinematic models of oblique faulting: Loma Prieta versus Parkfield-Coalinga. *Geophysical Research Letters*, *17*, 1453–1456. https://doi.org/10.1029/GL017i009p01453

Molnar, P. (1992). Brace–Goetze strength profiles, the partitioning of strike-slip and thrust faulting at zones of oblique convergence, and the stress–heat flow paradox of the San Andreas Fault. In *Fault Mechanics and Transport Properties of Rocks*, (pp. 435–459). New York: Academic Press.

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 pp.

Muñoz-Martín, A.; Álvarez, J., Carbó, A., De Vicente, G., Vegas, R. & Cloetingh, S.P.A.L. (2004). La estructura de la Corteza del antepaís Ibérico. In: Vera, J. A. (Ed.) *Geología de España*. SGE-IGME, Madrid (pp. 591-596).

Muñoz-Martín, A., De Vicente, G., Fernández-Lozano, J., Cloetingh, S. A. P. L., Willingshofer, E., Sokoutis, D., & Beekman, 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*(3-4), 298–314. https://doi.org/10.1016/j.tecto.2010.09.036

Pais, J., Cunha, P. P., Pereira, D., Legoinha, P., Dias, R., Moura, D., et al. (2012). *The Paleogene and Neogene of Western Iberia (Portugal). A Cenozoic record in the European Atlantic domain*. Springer Briefs in Earth Sciences, Springer, Berlin Series ID: 8897, 158 pp; DOI: https://doi.org/10.1007/978-3-642-22401-0

Pimentel, N.L. (1997). O Terciário da Bacia do Sado. Sedimentologia e análise tectono-sedimentar. *Ph.D. Thesis, Univ. Lisboa*, 381 pp.

Pimentel, N. L. (1998). Tectono-sedimentary evolution of the Sado Basin (Tertiary, southern Portugal). *Comunicações do Instituto Geológico e Mineiro*, *84*(1), 145–148.

Portero, J. M., & Olivé, A. (1983). El Terciario del borde meridional de Guadarrama y Somosierra. *Libro Jubilar homenaje a J.M. Ríos*, *2*, 527–534.

Pous, J., Muñoz-Martín, A., Olaiz, A. J., Seillé, H., & de Vicente, G. (2012). Análisis de la estructura alpina de la corteza del centro de la Península Ibérica: Una sección Magneto-Telúrica a través del Sistema Central (Sierra de Gredos). *Geo-Temas*, *13*, 4–8.

Quintana, I., Pulgar, J. A., & Alonso, J. L. (2015). Displacement transfer from borders to interior of a plate: A crustal transect of Iberia. *Tectonophysics*, *663*, 378–398. https://doi.org/10.1016/j.tecto.2015.08.046

Rasmussen, E. S., Lomholt, S., Andersen, C., & Vejbæk, O. V. (1998). Aspects of the structural evolution of the Lusitanian Basin in Portugal and the shelf and slope area offshore Portugal. *Tectonophysics*, *300*, 199–255. https://doi.org/10.1016/S0040-1951(98)00241-8

Reguzzoni, M., & Sampietro, D. (2015). GEMMA: An Earth crustal model based on GOCE satellite data. *International Journal of Applied Earth Observation and Geoinformation*, *35*, 31–43. https://doi.org/10.1016/j.jag.2014.04.002

Ribeiro, A., Cabral, J., Baptista, R., & Matias, L. (1996). Stress pattern in Portugal mainland and the adjacent Atlantic region, West Iberia. *Tectonics*, *15*(2), 641–659. https://doi.org/10.1029/95TC03683

Ribeiro, A., Kullberg, M. C., Kullberg, J. C., Manuppella, G., & Phipps, S. (1990). A review of Alpine tectonics in Portugal: Foreland detachment in basement and cover rocks. *Tectonophysics*, *184*(3-4), 357–366. https://doi.org/10.1016/0040-1951(90)90448-H

Ribeiro, O. (1940). *Observations géologiques et morphologiques dans les environs de Vila Velha de Ródão (Portugal)*. Paris: Rév. Géogr. Phys. Et de Géol. Dynam.

Ribeiro, O. (1941). Problemas morfológicos do Maciço Hespérico português. *Las Ciências, Madrid, año VI*, *2*, 315–336.

Rubio-Ordoñez, A., García-Moreno, O., & Bea, F. (2016). Nuevas aportaciones a la datación cronológica de los granitos de Cabeza de Araya, (Cáceres). *Geo-Temas*, *16*(2), 63–66.

Sequeira, A., Cunha, P. P., & Sousa, M. B. (1997). A reactivação de falhas, no intenso contexto compressivo desde meados do Tortoniano, na região de Espinhal-Coja-Caramulo (Portugal Central). *Comunicações do Instituto Geológico e Mineiro, Lisboa*, *83*, 95–126.

Serpelloni, E., Faccenna, C., Spada, G., Dong, D., & Williams, S. D. P. (2013). Vertical GPS ground motion rates in the Euro-Mediterranean region: New evidence of velocity gradients at different spatial scales along the Nubia-Eurasia plate boundary. *Journal of Geophysical Research: Solid Earth*, *118*, 6003–6024. https://doi.org/10.1002/2013JB010102

Spakman, W., & Wortel, A. (2004). Tomographic view on Western Mediterranean Geodynamics. In W. Cavazza, F. Roure, W. Spakman, G. M. Stampfli, & P. Ziegler (Eds.), *The TRANSMED atlas. The Mediterranean region from crust to mantle*, (pp. 31–52). Berlin Heidelberg: Springer-Verlag.

Tejero, R., Garzón Heydt, G., Babín Vich, R., & Fernández García, P. (2010). Long-term evolving "tectonic" landscapes within intra-plate domains. The Iberian Peninsula. Horizons. In *Earth science research, 2. Cap*, (Vol. 4, pp. 103–124). Hauppauge, NY: Nova Publishers Inc.

Torne, M., Fernàndez, M., Vergés, J., Ayala, C., Salas, M. C., Jimenez-Munt, I., & Díaz, J. (2015). Crust and mantle lithospheric structure of the Iberian Peninsula deduced from potential field modeling and thermal analysis. *Tectonophysics*, *663*, 419–433. https://doi.org/10.1016/j.tecto.2015.06.003

Torres, T., Ortiz, J. E., & Arribas, I. (2006). El anticlinal y las discordancias de Pareja (Guadalajara): definición de las unidades cenozoicas de la Depresión Intermedia (provs. Cuenca y Guadalajara, España). *Estudios Geológicos*, *62*(1), 89–102.

Vegas, R. (1975). Wrench (transcurrent) fault system of the southwestern Iberian Peninsula, paleogeographic and morphostructural implications. *Geologische Rundschau*, *64*(1), 266–278.

Vegas, R. (2000). The intrusión of the Plasencia (Messejana) dike as part of the Circum-Atlantic Early Jurassic magmatism: Tectonic implications in the southwestwern Iberian Peninsula. *Geogaceta*, *27*, 175–178.

Vegas, R., & Suriñach, E. (1987). Engrosamiento de la corteza y relieve intraplaca en el centro de Iberia. *Geogaceta*, *2*, 40–42.

Vegas, R., Vázquez, J. T., Suriñach, E., & Marcos, A. (1990). Model of distributed deformation, block rotations and crustal thickening for the formation of the Spanish Central System. *Tectonophysics*, *184*, 367–378. https://doi.org/10.1016/0040-1951(90)90449-I

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), 245-248.

Vergés, J. (1999). Estudi geològic del vessant sud del Pirineu oriental i central. Evolució cinemàtica en 3D. Servei Geològic. *Monografia Tècnica*, *7*, 192.

Villamor, M. P. (2002). Cinemática terciaria y cuaternaria de la falla de Alentejo-Plasencia y su influencia en la peligrosidad sísmica del interior de la península ibérica. *PhD Thesis. Universidad Conplutense de Madrid*, 343 pp.

Warburton, J., & Alvarez, C. (1989). A thrust tectonic interpretation of the Guadarrama Mountains, Central Spain. *Asociacion de Geologos y Geofisicos Espanoles del Petroleo. Libro Homenaje a Rafael Soler*, 147–155.

Wu, J. E., McClay, K., Whitehouse, P., & Dooley, T. (2009). 4D analogue modelling of transtensional pull-apart basins. *Marine and Petroleum Geology*, *26*, 1608–1623. https://doi.org/10.1016/j.marpetgeo.2008.06.007

Zoback, M. D., Zoback, M. L., Mount, V. S., Suppe, J., Eaton, J. P., Healy, J. H., et al. (1987). New evidence on the state of stress of the San Andreas fault system. *Science*, *238*, 1105–1111. https://doi.org/10.1126/science.238.4830.1105