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The "Castilian bend" of Rudolf Staub (1926): historical perspective of a forgotten orocline in Central Iberia

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Abstract The existence of an orogenic arc in the Variscan belt of Central Iberia is traced from its first recognition by the Swiss geologist, Rudolf Staub, at the XIV International Geological Congress (Madrid 1926), to the present. A review of the literature exposes the main facts related to Staub's original interpretation, and its subsequent discussion, rejection and rehabilitation in the 21st century. The "Castilian bend" or Central Iberian arc is defined as a secondary orocline formed during late stages of the Variscan orogeny, with a curvature opposite to that of the better known Ibero-Armorican arc. It bends the older Variscan, structures, the magnetic anomalies, and the stratigraphic, metamorphic, and magmatic zonation of the Iberian Massif. The original NE–SW trend of these elements has been preserved by porphyroblast inclusion trails that maintained constant orientations during the formation of both oroclines. The rediscovery of the Central Iberian arc has given a new impulse to research in the Iberian Massif during the last decade, which we briefly review. A short discussion is also included of remaining unknowns regarding the precise geometry and formation mechanism of the arc, and the new perspectives it opens for future research in the Variscan belt.

Keywords Curved orogens · Oroclines · Central Iberian arc · Iberian Massif · Variscan belt · Spain

1 Introduction

Curved orogens, arcs, bends, virgations, and oroclines are common features of orogenic belts. They can have different origins, in most cases open to debate, but the first step towards knowledge of a particular arc is identification. Recent arcs are primarily delineated by the orography, as is the case of the Western Alps, Carpathians, Himalayas or the Bolivian bend in the Andes, but once the high relief has been eroded, their recognition relies on the curvature of major structures and of geophysical anomalies.

The existence of an arc in the northern Iberian Massif, known as the "Asturian knee", was made evident for the first time on a map published by Guillermo Schulz (1858). The map showed Devonian beds and Carboniferous limestones delineating an arc with its concave side towards the east (Truyols and Marcos 1978).

Eduard Suess (1888), in the second volume of "Das Antlitz der Erde", considered the Iberian Cordillera as a possible fragment of the Armorican arc, based on the same age of tectonic movements and similarities with the terrains of Cornwall and Brittany. Although several hypotheses have been held regarding the correlation of Hercynian structures between the Iberian and Armorican Massifs, the Asturian arc has been fully accepted since the work of Suess as representing the core of the Armorican or Ibero-Armorican arc (Stille 1924, 1951; Kossmat 1921; Lotze 1929, 1954–1955; Carey 1955; Bard et al. 1971).

Another arcuate structure, however, was also proposed, occupying a more central position in the Iberian Massif, but never reached full acceptance and remained largely

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ignored during the second half of the 20th century. This contribution tells the history of knowledge of this arc, from its early discernment by Rudolf Staub in 1926, through the contributions that challenged or supported its existence, until recent times, when it has received a new, perhaps definitive, impulse.

2 The "kastilische Beugung" ("Castilian bend") of Rudolf Staub

2.1 The XIV international geological congress and the "Gedanken zum Strukturbild Spaniens" (thoughts on spanish tectonics)

The XIV International Geological Congress was organized in Spain in 1926, with sessions taking place from 23 to 31 May in Madrid. It was the second to be held after the First World War and, using the words of Ayala-Carcedo et al. (2005), "It was Spain that benefited most from the XIV IGC and probably never again there has geology received so much public and official attention". One of its scientific sessions was devoted to the Hercynian folding and another to the Geology of Africa and its relationship with the European geology. Moreover, "Tectonics, a field previously underdeveloped in Spain, benefited from the presence of tectonicists such as Fallot, Stille, and Staub" (Ayala-Carcedo et al. 2005).

Rudolf Staub, a Swiss geologist whose research focused on the Alps, was mainly interested in Alpine tectonics. His prime objective in the Iberian Peninsula was the Betic Cordillera, but he also paid attention to the structure of the Iberian Meseta. He came in touch with Antonio Carbonell Trillo-Figueroa, a Spanish mining engineer who led two of the pre-Congress field trips, on the tectonics of the Guadalquivir River Valley and the Betic mountains, and was also one of the main contributors to the XIV IGC with five papers (Ayala-Carcedo et al. 2005). At the Congress, Staub presented his "Gedanken zum Strukturbild Spaniens" (Thoughts on Spanish Tectonics), based on his analysis of the Geological Map of Spain edited by the Instituto Geológico de España in 1919—which he qualified as excellent– and probably on observations made during the field trips of the XIV IGC, or other trips, perhaps guided by Carbonell. This work was reprinted several times (Staub 1926a, 1926b, 1928a), including a translation to Spanish by Carbonell (Staub 1927), who wrote the prologue and also published a short communication summarizing Staub's ideas (Carbonell 1927). The Spanish version (Staub 1927) included Staub's (1926b) map of the Iberian Peninsula (reproduced here in Fig. 1), approximately at a scale 1:3000000, and added a schematic cross section of the Betic Cordillera at a scale 1:370000.

In the section devoted to the old Meseta, Staub (1926a, 1928a) distinguished three large units: an Archaean block in the core, a possible belt of disrupted Caledonian chains, and the Spanish Hercynides. The two latter units were supposed to surround the Archaean core, although he did cast doubts on the existence of the Caledonian chains. The Archaean massif (also referred to as the old block or Galician block) corresponds to the high-grade rocks of Galicia and northern Portugal, the Spanish Central System, and the Toledo Massif. The so-called Hispánides (comprising the old Caledonian and Hercynian chains) would form two branches, located to the north and south of the old block, and were considered to connect with each other in a large east-closing bend partially hidden by the Tertiary basins of Castilla la Nueva. Staub remarked that "Die paläozoischen Ketten Asturiens schwenken vielmehr an der Ecke von Sigüenza und den Montes de Toledo in einer gewaltigen Beugung um die archäische Ecke der Sierra de Guadarrama nach Westen und Westnordwesten um und ziehen geschlossen nach Portugal und in den Ozean hinein" (The Palaeozoic chains of Asturias rather curve in the region of Sigüenza and the Montes de Toledo in an impressive bend around the Archaean area of Sierra de Guadarrama back to the west and northwest and then running straight through to Portugal and into the ocean).

The bend was called the "kastilische Beugung" ("Castilian bend"), and Staub stated that "Die Hercyniden Europas biegen in Spanien um diesen archäischen Block nach Westen zurück, sie dringen nicht nach Afrika hinein" (The European Hercynides in Spain swing around the Archaean block back to the west, without penetrating into the interior of Africa).

In his book "Der Bewegungsmechanismus der Erde dargelegt am Bau der irdischen Gebirgssysteme" (The mechanics of the Earth underlying the structure of the world's mountain systems; Staub 1928b), the author included in his Fig. 34 a sketch map of the European Hercynides, where he shows the "Castilian bend", cored by the Celtiberic massif, and followed to the east by the Armorican and Variscan (Bohemian) arcs. Another map in the same book (his Fig. 39) depicts the relationships among the Alpine trends in Europe and those of the Variscan belt, showing the imprint of the underlying basement in the Alpine structures of eastern Iberia.

The "Castilian bend" was subsequently included by Holmes (1929), together with the Asturian arc, in a sketch of the Palaeozoic fold systems of the opposing lands of the Atlantic, also reproduced by Du Toit (1937). The latter author also published a sketch of the Palaeozoic fold systems crossing the North Atlantic Ocean where the "Castilian bend" is clearly depicted.

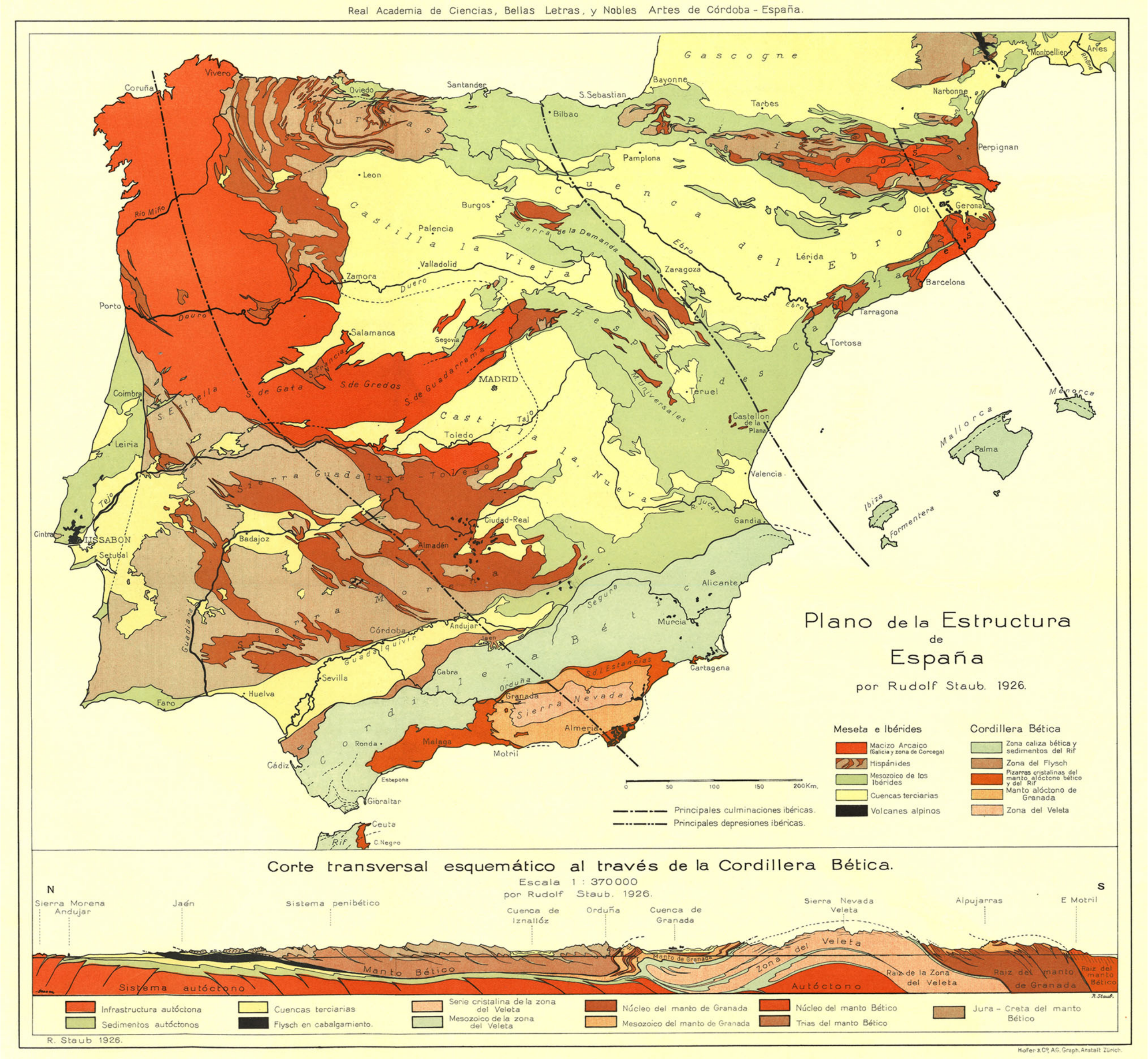

Fig. 1 Map of the Iberian Peninsula enclosed in Staub (1927). The original has 45 × 43 cm and is drawn approximately to the scale 1:3000000

2.2 Discussion and rejection by Franz Lotze

Hans Stille, full professor of the University of Göttingen at the time, participated also in the XIV International Geological Congress, with a communication that related the near perpendicular fold trends in northern and southern parts of the Iberian Peninsula with the contrast between the Rhenides of northern Europe and the Gondwanides in the south (Stille 1926). The proposal by Staub of joining both trends by an arcuate structure should have been rather surprising to Stille, who the following year discussed and rejected Staub's interpretation of an Archaean core in the Iberian Meseta (Stille 1927).

However, it was Stille's former pupil Franz Lotze who would discuss the "Castilian bend" of Staub in more detail. Shortly after completing his doctorate with Stille in 1928, Lotze published his "Stratigraphie und Tektonik des keltiberischen Grundgebirges, Spanien" (Stratigraphy and Tectonics of the Celtiberian Basement of Spain; Lotze 1929; see Lotze 1954–1955 for the Spanish translation), in which he criticised Staub's hypothesis based largely on the non-existence of the Archaean block. First, he (correctly) interpreted the gneisses of the Sierra de Guadarrama as Palaeozoic and assumed a similar age for many other Spanish gneisses, although acknowledging the possibility that some were Archaean. He also pointed out that the

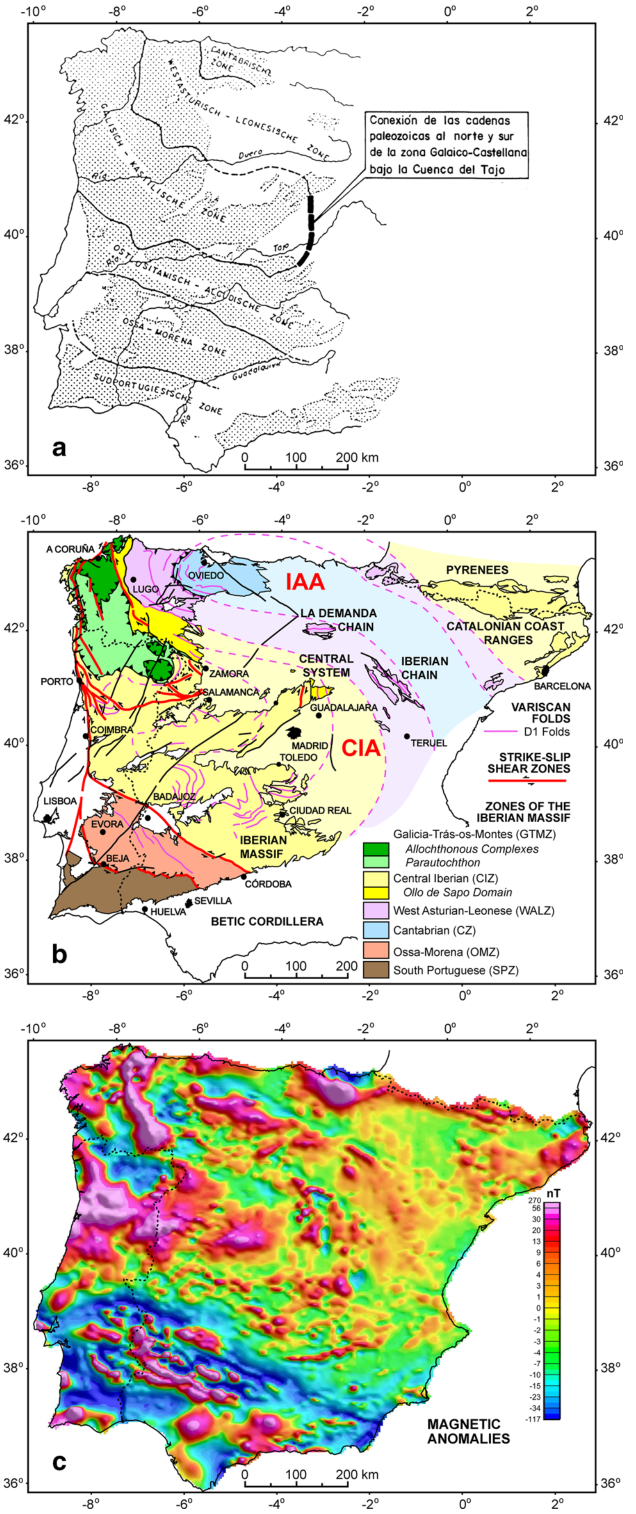

Fig. 2 **a** Subdivision of the Iberian Meseta by Lotze (1945b) ▶ modified by Querol Muller (1989) by adding the heavy dashed line. The original text box in Spanish reads "Connection between the Palaeozoic chains to the north and south of the Galician-Castilian zone under the Tagus basin". Coordinates and scale have been added. **b** Map of the Variscan basement in the Iberian Peninsula and the subdivision in zones of the Iberian Massif, based on Julivert et al. (1972) and Farias et al. (1987). The axial traces of the first Variscan folds and the main strike-slip shear zones are also shown, as well as the assumed continuations of the CZ, WALZ, and CIZ under the Mesozoic and Cenozoic cover. Arcs: *CIA* Central Iberian, *IAA* Ibero-Armorican. **c** Map of the magnetic anomalies in the Iberian Peninsula. Data from Ardizone et al. (1989) and Miranda et al. (1989)

numerous granite apophyses intruding the gneisses are Carboniferous, casting doubts on the existence of the old block. Then, Lotze discussed the continuation of the folds of Guadarrama, which according to him should be found in the Montes Universales, east of Madrid, instead of in the Montes de Toledo, to the south. He recognized the dominant E-W fold trend in the Montes de Toledo, but attributed it to an anomalous attitude of the chain there, a local deflection in an overall NW–SE running belt. In that, he followed earlier interpretations of Suess (1888), Kossmat (1921), and Stille (1924), and denied the existence of the "Castilian bend", and that Variscan folds entering the Peninsula in the northwest curved back towards Portugal and the Atlantic Ocean. For him, the continuation of these folds should be sought in the Moroccan Meseta.

Meanwhile, Staub's ideas were essentially accepted by Wilfried von Seidlitz, of the same generation as Hans Stille and full professor at the University of Jena (von Seidlitz 1931). This prompted Lotze (1945a, 1950a for the Spanish translation) to take up the discussion again. In a new communication, he extended his arguments against an Archaean age of the northwest and central parts of the peninsula, stated that no Archaean rocks were known in Iberia, and discarded any Caledonian deformation events. Although he did not explicity discuss the "Castilian bend", he published in the same volume the division of the Variscides of the Iberian Meseta (Lotze 1945b, 1950b for the Spanish translation), where he drew the different zones in Central and Southern Iberia all parallel to each other with an approximately WNW–ESE trend (Fig. 2a).

2.3 The "Castilian bend" in Central Iberia: falling into oblivion

Following Lotze's work, the arcuate structure described by Staub was practically consigned to oblivion. An exception was the communication by Llopis Lladó and Sánchez de la Torre (1962) supporting Staub's idea of an old shield in Central Spain, although assigning a Carelian (Neoproterozoic) age to the recumbent folds of the Toledo region, subsequently overprinted by the Hercynian metamorphism. Later, Llopis Lladó (1966) proposed that the Palaeozoic basins occupied roughly the same position as their present outcrops, between the old Precambrian shields. This would imply the existence of several narrow Precambrian massifs, but also of some wide ones, such as Hesperia and Douria-

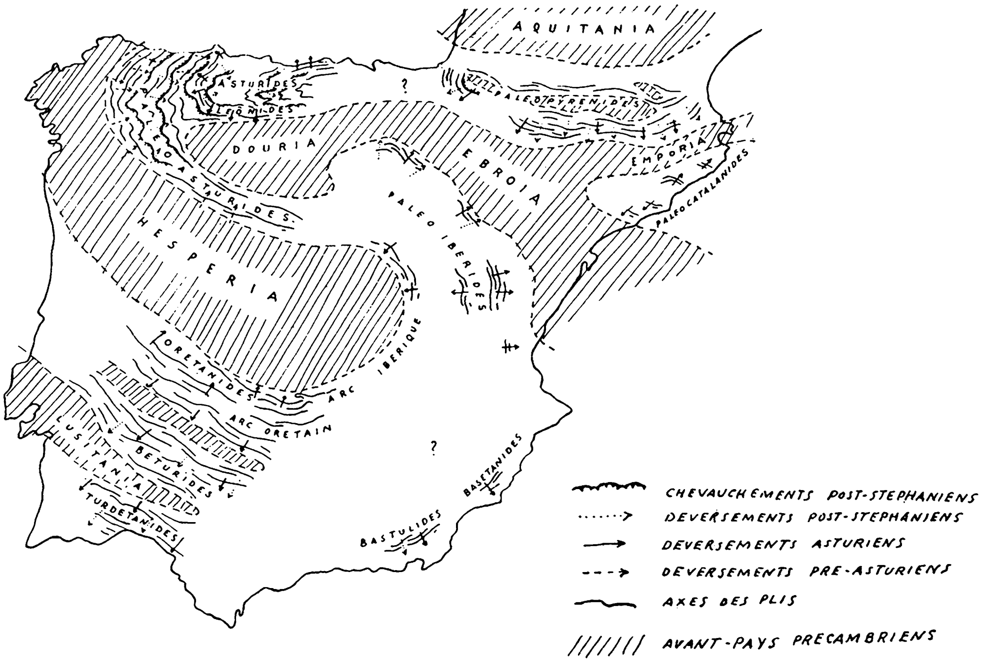

Fig. 3 Tectonic sketch of the Iberian Hercynides by Llopis Lladó (1966). *White* represents the Hercynian sedimentary basins

Ebroia (Fig. 3). He drew the “Castilian bend”, which he called the Iberian arc for its main part, and the Oretanian arc for its southeastern part, and also included the Asturian arc, although drawing its continuation in the Pyrenees.

This option, as an alternative to the correlation with Brittany, was initially supported by Matte (1968), who correlated the northern continuation of the Galician virgation with the basement of Aquitaine. It is ironical that, while working on the “virgation hercynienne de Galice”, Matte cited the work of Staub (1926b) only in relation with the proposed existence of an Archaean block, without mentioning the other “virgation” he had described, the “Castilian bend”.

However, Matte changed his mind concerning the continuation of the northwestern Iberian structures shortly afterwards in Bard et al. (1971). This work firmly established a correlation with the Armorican Massif and introduced the name “Ibero-Armorican virgation”. Based on the distribution of sedimentary facies, the authors divided the Iberian Massif in nine zones, most of which could be continued in western France. They also established a tectonic zoning across the Bay of Biscay, and did the same with the metamorphic belts and the Variscan granitoids.

The following year, Julivert et al. (1972) published the tectonic map of the Iberian Peninsula and the Balearic Islands, followed by a memoir printed eight years later (Julivert et al. 1980). These authors proposed a new division of the Iberian Meseta, based on the zones of Lotze (1945b, 1950b), but advances in the geological knowledge of Iberia allowed them to define the zone boundaries more precisely. The tectonic map of Julivert et al. (1972) shows the Variscan structural trends delineating the Asturian arc together with the Galician virgation, but striking NW–SE in Central Iberia. Later, Farias et al. (1987) proposed a new Galicia-Trás-os-Montes Zone, based on subdivisions by Matte (1968) and Ribeiro (1974), and which includes the allochthonous complexes of Northwest Iberia (Fig. 2b). These changes were incorporated in the tectonic map of the Iberian Peninsula, published to scale 1: 2000000 as part of a book on Spanish geology (Rodríguez Fernández et al. 2004). But none of these maps included the “Castilian bend” of Staub (1926a).

2.4 The struggle for recognition

During decades, the arc in Central Iberia remained ignored, despite suggestions of its presence in a series of manifestations that were interpreted in different ways or not interpreted at all. For instance, the above-mentioned contribution of Bard et al. (1971) included a sketch with the magmatic zones defined by different types of Variscan granitoids. In northwestern Iberia, they delineated a tight arc closing towards the southeast (Fig. 4a). The zoning was attributed to differences in pressure of regional metamorphism, but the significance of the arcuate shape was not addressed. Although the zoning is not realistic, it reflects the concentration of granitoids at the core of the arc (Fig. 4b), which has been linked to the pressure attained by regional metamorphism (Martínez Catalán et al. 2014). The pressure was higher there due to the emplacement of the Galicia-Trás-os-Montes Zone (GTMZ), a thick nappe stack of allochthonous units. The GTMZ occupies the core of

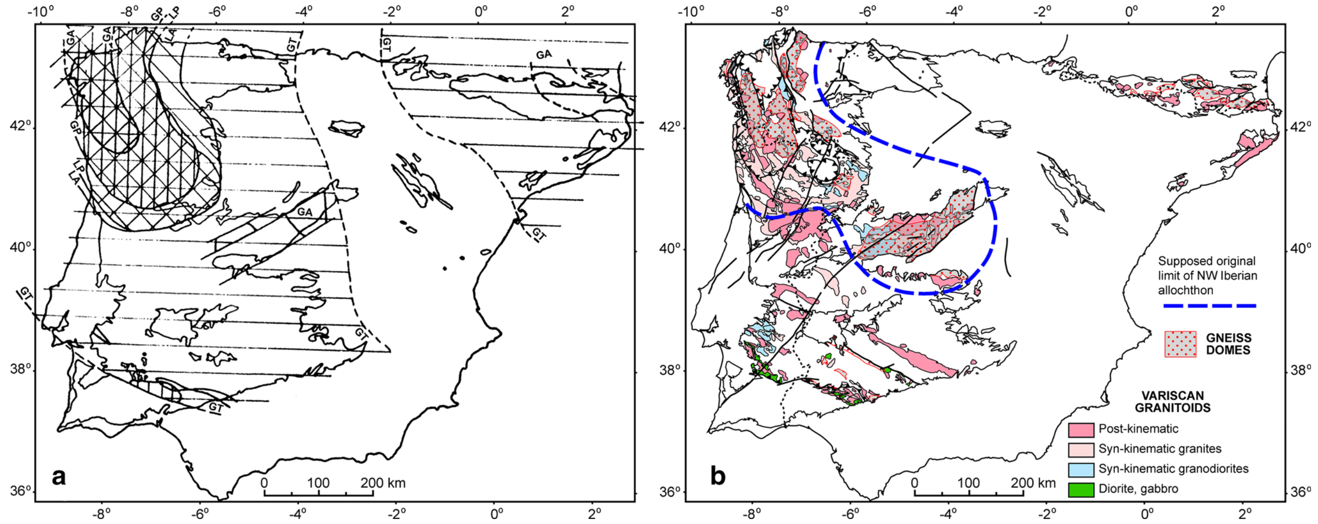

Fig. 4 **a** Distribution of different types of granitoids in the Iberian Peninsula, after Bard et al. (1971). *GA* autochthonous anatectic granodiorites, *LP* parautochthonous leucogranites, *LA* allochthonous leucogranites, *GP* early granodiorites, *GT* late granodiorites. Coordinates and scale have been added. **b** Distribution of Variscan gneiss domes and granitoids in the Iberian Massif. The *dashed line* enveloping the gneiss domes and abundant synkinematic granitoids probably marks the original limit of the northwest Iberian allochthon

Staub's "Castilian bend", although by the time it was proposed by Farias et al. (1987), and for many years afterwards, the geometry of the GTMZ was not related to the existence of an arc.

López Plaza and Gonzalo (1986) found that many synkinematic granitoids in northwestern and central Iberia form relatively flat, inclined bodies, with low-dipping planar and linear fabrics that can be related to tectonic flow and be used as indicators of the structural evolution. They defined vergence as opposite to the dip or plunge direction of their fabrics, and also based on the polarity of different granitic facies resulting from magmatic differentiation. The authors included a structural sketch of the Iberian Massif where the vergence of granitoids is plotted together with that of folds and thrusts. Both show centrifugal vergences, and the line separating opposite vergences in granitoids, called the axial zone, coincides with the axial trace of Staub's "Castilian bend".

Hints of an arcuate structure existed mainly in Central and Southeast Iberia, in the form of N-S trends of Variscan folds in the eastern part of the Spanish Central System north of Guadalajara, and also between Toledo and Ciudad Real as already noticed by Staub (1926a, b, 1927, 1928a) and Llopis Lladó (1966). For instance, Castro (1985) defined a Central Iberian block extruded to the east between a sinistral shear zone to the north, and a wide dextral band of distributed deformation to the south. The block has a curved limit concave to the east that reflects the geometry of the arc in Central Spain, although it does not include the allochthonous units of Northwest Iberia at its core.

Between the years 1983–1989, studies were carried out on the Tagus basin by students of the Escuela Técnica Superior de Ingenieros de Minas (School of Mining Engineering) of Madrid, including one Ph.D. Thesis (Lanaja del Busto 1987). These integrated surface geology, geophysics and well data in areas to the north, northeast and east of Madrid. The geophysics and well data had been acquired between 1963 and 1983 by exploration and oil companies (Valdebro, Amospain, Auxini, Tenneco and Shell) searching for hydrocarbons, a fruitless effort which ended with the release of the data to the Spanish Ministry of Industry and Energy. A synthetic report was written by Ramón Querol Muller, Director of the Instituto Geológico y Minero de España (IGME, the Spanish Geological Survey) between the years 1985–1987. The report (Querol Muller 1989) was accompanied by 14 foldouts including a 1:200000 geological map, a sheet with well logs, three with stratigraphic correlations between well logs and columns recorded in the field, one with eleven seismic lines, two with isochrones (TWTT) for two characteristic stratigraphic horizons seen in the seismic profiles, one with the Bouguer anomaly, another with its interpretation, two magnetic maps, and two maps with isobaths to the base of the Cretaceous Utrillas Fm. and the basement respectively.

Most of the report, of which several copies were printed but remained unpublished, is devoted to stratigraphy, although geophysics also receives significant attention. A short section deals with the structural interpretation, which is centred in post-Variscan tectonics. Querol Muller (1989) concluded that gravimetric and magnetic anomalies reflecting the structure of the basement have a N–S trend that reflects the connection between the Palaeozoic chains to the north and south of Lotzés (1945b) Galician-Castilian Zone. In his own words: “In this way, the E–W lineaments of the Montes de Toledo, south of that (Galician-Castilian) massif, cross the Tagus Basin beneath its sedimentary cover, pass through the N–S striking slate-rich outcrops of the Central System, and join the Palaeozoic lineaments of the Zamora and León provinces”. He cited Llopis Lladó (1966) as having postulated the same connection (Fig. 3), and included Lotze’s (1945b) figure with the zones of the Iberian Peninsula, to which he added his own interpretation (thick dashed line on Fig. 2a).

The same year when Querol Muller wrote his report, the Instituto Geográfico Nacional (IGN) published the aeromagnetic map of Spain. The residual anomalies (Ardizone et al. 1989) show a rather regular curvature in Central Eastern Spain, where the Variscan basement is mostly covered. A recent version, based on aeromagnetic data by Ardizone et al. (1989) and Miranda et al. (1989), includes the whole Iberian Peninsula. Both versions are available from Geomagnetic Data of the IGN website, and a colour and shaded relief plot is shown in Fig. 2c. The more important magnetic anomaly in terms of wavelength and amplitude delineates a tight fold at the core of the arc. Its northern limb is formed by a magnetic lineament centered in the city of Lugo, attributed to magnetite-bearing migmatites and inhomogeneous granites developed during extensional collapse in the Lugo dome (Ayarza and Martínez Catalán 2007).

3 Rediscovery of the arc in Central Iberia

3.1 The beginning of the 21st century

Staub (1926a, b) “Castilian bend” was unexpectedly resuscitated by Aerden (2004), who measured the orientation of inclusion trails in 30 samples of porphyroblastic schist, collected over ca. 500 km distance between the northern Galician coast and the Iberian Central System. Four sets of Foliation Intersection Axes (FIA; Bell et al. 1995) defined by the inclusion trails and by matrix foliations were distinguished on the basis of their specific trends and consistent relative timing relationships. The thus established FIA-trend sequence (E–W, NNW–SSE, NE–SW, and WNW–ESE) appeared to be independent of the location of samples in the Ibero-Armorican arc. This remarkable consistency of inclusion-trail orientations reproduced similar reports made previously in other Variscan regions (Aerden 1995, 1998), the Appalachians (Hayward 1992; Bell et al. 1998), the Imjingang belt in South Korea (Jung et al. 1999) and, significantly, in another orocline: the Proterozoic Kimberley arc of Northwest Australia (Bell and Mares, 1999). Aerden (2004) noticed further that his FIA sequence is mirrored in several data sets for (polyphase) field structures in Northwest Iberia, and on that basis proposed a new correlation of various types of regional-scale fold-interference patterns in the Iberian Massif. It implied the presence of a partially blind, east-closing orocline in Central Iberia (Fig. 5), which he then looked for and saw confirmed on an aeromagnetic map of Spain (Ardizone et al. 1989; see Fig. 2c).

Meanwhile, Carreras faced the problematic place of the Northeast Iberia segment of the Variscides (central and eastern Pyrenees and Catalonian Coast Ranges). This led him to propose a new link with surrounding Variscan domains (i.e. Iberian Massif, Montaigne Noire and Sardinia) at the Philippe Matte symposium, held in September 2007 in Orléans (France). His model was based on two main thoughts: (1) The Variscan belt in Northeast Iberia delineates an arcuate belt with more internal, deep-seated domains in the north and external, shallow-seated domains in the south (Carreras and Cirés 1986), that does not fit with the external location proposed for it (e.g. Matte 1968, 2007). (2) During the structural evolution, there was a gradual change from WSW–ENE to NW–SE trends, associated to a change from compression-dominated to wrench-dominated dextral transpression. This crustal-scale strain partitioning led to the formation of arcs in a similar way as back rotation folds form between ductile shear zones (Harris 2003), giving rise to changes in the dominant trend in Northeast Iberia from SW–NE to NW–SE.

Scattered outcrops showing shallow-seated Variscan rocks in the southeast of the Iberian Chain, and N-S trending structures in eastern Guadarrama suggested the existence of an arcuate structure on the eastern part of the Central Iberian Zone to Carreras, who was also aware of the curvature of magnetic anomalies in the map of Ardizone et al. (1989). Indirect arguments for the curvature and eastern closure of this zone are provided by the control of basement structures on the overlaying trend of alpine structures. The rotation from NW–SE trend of the Iberian Chain towards the WSW–ENE trend of the Betic Cordillera can be viewed partially as resulting from this basement control.

A zoom-out view of the Variscides reveals that these arcuate arrangements abound and correspond to an alternation of WSW–ENE domains with NW–SE domains dominated by transpressional strike-slip (e.g. South Armorican Zone, Bray Fault, Elbe Fault), as proposed by Carreras and Druguet (2012, 2014).

3.2 Present stage: the recent works

The division established by Julivert et al. (1972), which did not include the arc in Central Iberia, had a decisive

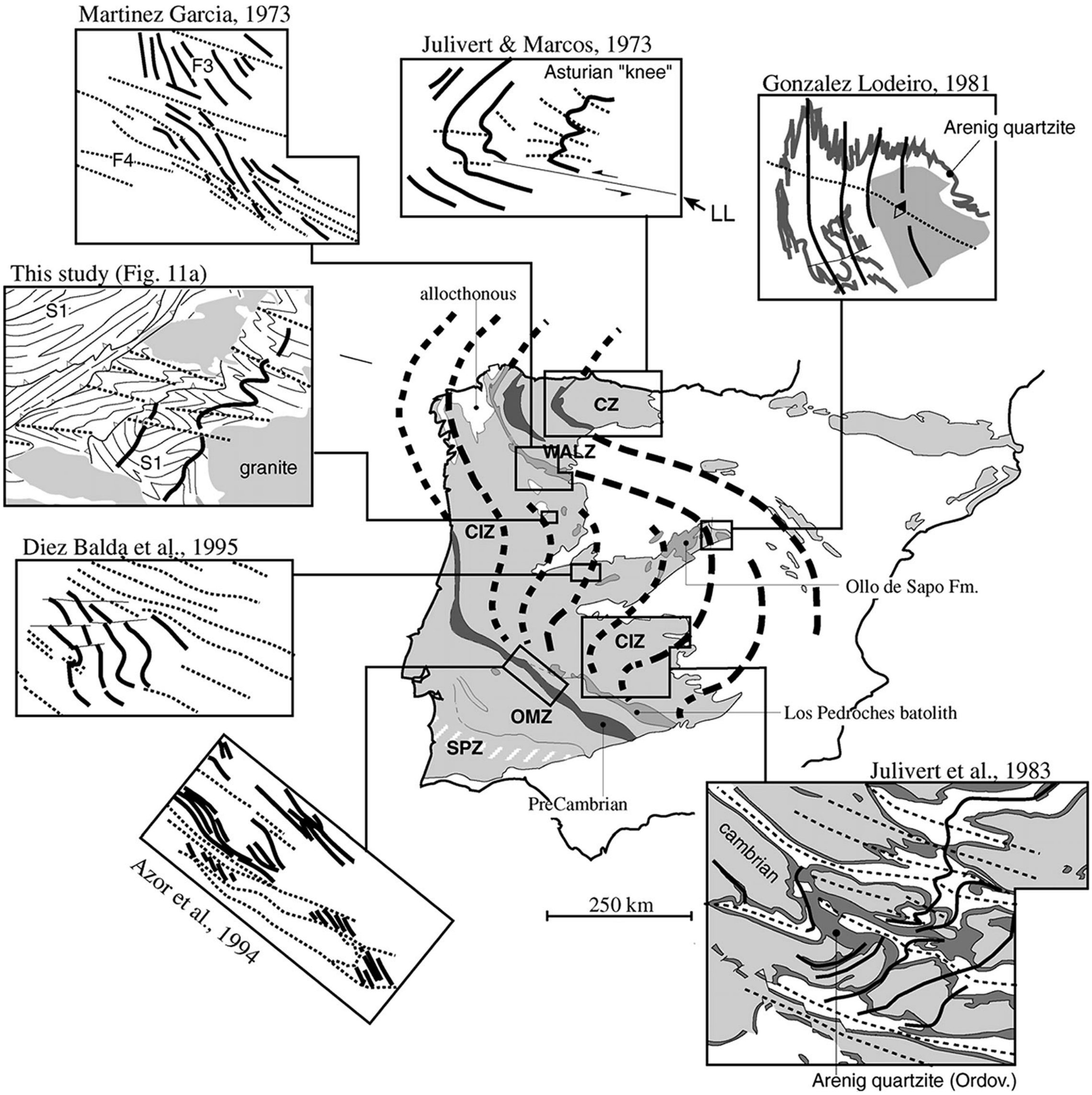

Fig. 5 Aerden's (2004) proposal of a large S-shaped orocline based on fold interference patterns mapped in different parts of the Iberian Massif. Reproduced with permission from Elsevier. *CIZ* Central Iberian Zone, *CZ* Cantabrian Zone, *LL* León Line (fault), *OMZ* Ossa-Morena Zone, *SP* South Portuguese Zone, *WALZ* West Asturian-Leonese Zone

influence in the following decades, during which the zone boundaries were only slightly modified and more accurately defined. Figure 2b depicts a recent version of the zoning of the Iberian massif, based on Julivert et al. (1972) and Farias et al. (1987), to which the trends of first Variscan folds have been added to show the geometry of the arcs.

The paper of Aerden (2004) and the communication of Carreras in 2007 took still a few years to be echoed, but the arc is progressively gaining acceptance. Martínez Catalán (2011, 2012) assumed Aerden's interpretation of the arc as having formed by fold interference at a large scale, and proposed the name "Central Iberian arc". He described its history in terms of the structural evolution of the Iberian Massif. A first set of folds pre-dated the arc, and was followed by thrusting and then by extensional collapse in the internal zones. Perhaps the arc nucleated during thrusting of the allochthonous complexes, but its development was younger, contemporaneous with a second generalized folding episode coeval with strike-slip tectonics at the scale of the Variscan belt.

Aerden (2011) presented two new sets of inclusion-trail data for the eastern part of the Spanish Central System, and the northern part of the Ossa-Morena Zone (Sierra Albarrana). Consistently NNE–SSW to NE–SW striking inclusion trails in these areas are overprinted by younger WNW–ESE striking ones. These directions match the trends of the youngest 2 FIA sets of Aerden (2004) in

Northwest Iberia, and further support late-stage bending of an originally more linear belt.

Meanwhile, the axial surface of the Central Iberian arc has been traced with increased precision in the more internal domains. Dias da Silva (2014), studying the relationships between the autochthon and parautochthon in the southeastern limit of the GTMZ, west of Zamora, found early folds trending NE–SW to N–S overprinted by NW–SE late folds, thus confirming that this region corresponds to the hinge zone of the Central Iberian arc.

Refolding of early Variscan folds and Variscan magnetic anomalies confirm that the Central Iberian arc fits the definition of Carey (1955) of an orocline, as a linear fold belt that was subsequently bent in map view acquiring a horseshoe shape. Additional arguments on the non-primary character of the arc are provided by analysis of sedimentary structures at its outer low-grade domains. Shaw et al. (2012) carried out a study in Early Ordovician platform facies sediments of Northern and Central Iberia, where they show that paleocurrent directions are often at high angle to Variscan structural trend. They describe their disposition as radial in relation to both the Ibero-Armorican arc and the Central Iberian arc, and propose a palinspastic restoration to a straight continental margin. In their paper, they include a redrawing of Du Toit's (1937) sketch of the Palaeozoic fold systems showing the two Iberian arcs.

4 Discussion: geometry, mechanisms and perspectives

This section will focus on two aspects for which available stratigraphic and structural data permit some discussion: the continuation of the tectono-stratigraphic zones defined in the northern part of the Iberian Massif to the southern branch of the Central Iberian arc, and the mechanism of arc formation. The aim is not to reach definitive conclusions, but to centre the debate and to discuss the perspectives opened by the arc.

4.1 Continuation of the Variscan zones along the Central Iberian arc

No Archaean block exists at the core of the arc, which instead corresponds to the more internal parts of the Variscan belt, composed of medium- to high-grade metamorphic rocks and a dense cluster of granitoids cropping out in Northwest and Central Iberia (Fig. 4b). In Northwest Iberia the core includes the allochthonous units of the GTMZ, consisting of continental and arc-derived peri-Gondwanan terranes as well as Palaeozoic ophiolites of the Rheic realm (Martínez Catalán et al. 2009).

Moreover, several large gneiss domes occur in the core domain (Fig. 4b), where upper amphibolite and granulite facies were attained during the extensional collapse. In the autochthonous Central Iberian and West Asturian-Leonese zones (CIZ and WALZ), peak pressures reached between 0.8 and 1.4 GPa, well in excess than those provided by the sedimentary pile (Barbero and Villaseca 2000; Díez Montes 2007; Alcock et al. 2009). Rubio Pascual et al. (2013) and Martínez Catalán et al. (2014) have suggested that the extra overburden was provided by the allochthonous nappe stack, preserved in the GTMZ but whose original extent could have reached as far as the present eastern part of the Spanish Central System (Fig. 4b).

The continuation of the WALZ and Cantabrian (CZ) zones brings to actuality the discussion addressed by Staub (1927) of whether the southern branch of the arc continues towards Portugal and the Atlantic Ocean, as he believed himself, or penetrates towards the interior of Africa, which is crucial to establish correlations with the rest of the Variscan belt in Central Europe and its continuation into Africa and the Appalachians.

The first Variscan folds delineate an open bend in the northern half of the arc, but in the southern branch, they are overprinted by younger WNW–ESE folds showing a complex interference pattern (Fig. 2b). Many magnetic lineaments show a reasonable correlation with the trend of the first Variscan folds, and depict also an open bend in most of the arc, except its southwestern limit, where the fold interference occurs.

Neither the stratigraphic sequence nor the thin-skinned style that characterizes the CZ are found in the south, and the continuation of this zone under the post-Variscan sediments is not suggested by the magnetic anomalies (Fig. 2c). Regarding the WALZ, its series are also different from those of the Southeast Iberian Massif, although not incompatible. The same counts for the structural styles, characterized by recumbent folds and thrusts in the north vs. steep folds in the south. Along-strike variations in the covered part might explain these changes, but the approximate continuation of the pre-arc structures indicated by aeromagnetic data suggests that the WALZ continues under the Mesozoic and Cenozoic cover but does not crop out to the south and southwest of the CIZ, or it does so only at its southeastern limit (Fig. 2b, c).

However, Shaw et al. (2012) trace the southern branch of the arc parallel to the boundary between the CIZ and Ossa-Morena Zone (OMZ), delineating an arc as tight as the one traced initially by Staub (1927). Their "Variscan outer hinterland fold and thrust belt", formed by the WALZ and its continuation in the southern limb of the arc, heads for the Atlantic Ocean, at odds with their statement that "the search for the continuation of the terranes that constitute the south limb of the Central Iberian Orocline first focus toward the south, in northern Africa".

A rather continuous negative magnetic anomaly delimits the curved magnetic lineaments of the CIZ to the south (Fig. 2c). This is a NW–SE straight feature that closely follows the northern boundary of the OMZ (Matachel fault; Azor Pérez 1997), and can be traced to the southeast, beneath the Betic Cordillera. Both the first Variscan folds and the magnetic anomalies in the CIZ are clearly oblique to this boundary. The arc, then, would not continue to the WNW, towards the Atlantic Ocean, but would head for the OMZ, having been displaced by the strike-slip shear zones that characterize this boundary. The continuation of the CIZ could be somewhere in northern Africa or southern Europe, reworked in one of the Alpine belts surrounding the Mediterranean. Or, alternatively, in the Variscan belt of Central Europe, displaced by one of the dextral strike-slip systems active during late stages of the Variscan collision (Shelley and Bossière 2000; Martínez Catalán 2011).

4.2 Mechanisms of formation of the arc

Mechanisms for the formation of primary and progressive arcs may include opposite shearing along their flanks, bending induced by collision with an indentor, and divergent flow, which can be related to gravitational collapse or lateral extrusion of the orogen (Schellart and Lister 2004). For secondary arcs (oroclines), the more important mechanisms are buckling by shortening parallel to the trend of the orogenic belt and transcurrent shearing of the two flanks with opposite kinematics (Ries and Shackleton 1976; Macedo and Marshak 1999; Weil and Sussman 2004).

For the Ibero-Armorican arc, progressive rigid-plastic indentation coeval with the main phases of the Variscan collision was proposed by Matte and Ribeiro (1975) and Matte (1986), based on the orientation of the deformation ellipsoids, the same tool used by Ries and Shackleton (1976), who however interpreted the arc as secondary and with a geometry similar to that of buckle folds. A combination of thrusting and sinistral strike-slip shearing in Southwest Iberia was invoked by Brun and Burg (1982) who, as Matte and Ribeiro (1975) interpreted the arc as progressive.

Buckling of a linear fold and thrust belt about a vertical axis has been proposed for the Asturian arc, based on a large set of palaeomagnetic data (Weil et al. 2000, 2010, 2013; Weil 2006; Pastor-Galán et al. 2011). These data demonstrate post-nappe oroclinal bending, and constrains its timing to the upper Pennsylvanian to earliest Permian (310–299 Ma).

Palaeomagnetic data in the Central Iberian arc are too scarce to be used for interpreting its origin. However, the Central Iberian arc bends the first Variscan folds and thrust faults, and it is therefore also interpreted as formed by folding about a vertical axis. Closure of the arc was accompanied by strong internal deformation giving rise to late folds (Fig. 5) with associated slaty or crenulation cleavage, and the resulting geometry approaches the tangential-longitudinal strain model for buckle folds (Martínez Catalán et al. 2014).

Folding of a previous linear belt suggests a change in orientation of the regional stress field. Not one, but three such changes were proposed by Aerden (2004) on the basis of his 4 FIA sets. The oldest E–W oriented FIA set (FIA_1) was found only in the allochtonous complexes and interpreted to record N–S plate convergence as early as 360 Ma. Subsequent FIA_2 and FIA_3 would have developed due to NNW–SSE and NW–SE directed crustal shortening, respectively, and gave the Variscan belt in Iberia a broadly NE–SW trend. The youngest FIA_4 formed during NNE–SSW crustal shortening subparallel to the preexisting orogen and created the two Iberian oroclines.

Aerden (2004), Martínez Catalán (2011, 2012), and Carreras and Druguet (2014) share the idea that the formation of both Iberian arcs was related to late-orogenic transpression, perhaps reflecting an increasing resistence to plate convergence during the Variscan collision. This is supported by the fact that late folds are axial planar to the arcs but coeval and closely linked to large-scale ductile shear zones.

Aerden (2004) proposed a synchronous origin of both arcs by sinistral transpression, based on (1) the existence of sinistral strike-slip faults at the southern boundary of the CIZ, (2) his interpretation of regional fold patterns (Fig. 5), and (3) the S-shaped geometry delineated by the magnetic anomalies (Figs. 2c, 6a). Carreras and Druguet (2014) and Martínez Catalán (2011) favour a context of dextral transpression (Fig. 6b, c), because dextral shear zones are dominant in the Variscan belt. For the latter author, the "S" delineated by the two Iberian arcs is not a reliable criterion because they are not coeval: the Ibero-Armorican arc would have closed later because it bends the axial traces of late folds that are axial planar to the Central Iberian arc. According to Aerden (2004), however, these folds do not represent a single set of continuous structures but two different generations (Fig. 5).

The model of Martínez Catalán (2011) involves dextral transcurrence kinematically equivalent to an intracontinental transform fault forming the Gondwana-Laurussia plate boundary at that time, and affecting the units of the northern margin of Gondwana. A compressive bridge inside this transcurrent system may have created the arcs in the Variscan belt (Fig. 6c).

Shaw et al. (2012) doubt whether the two Iberian arcs have a common origin or were formed by different geodynamic processes. They discard shearing along the

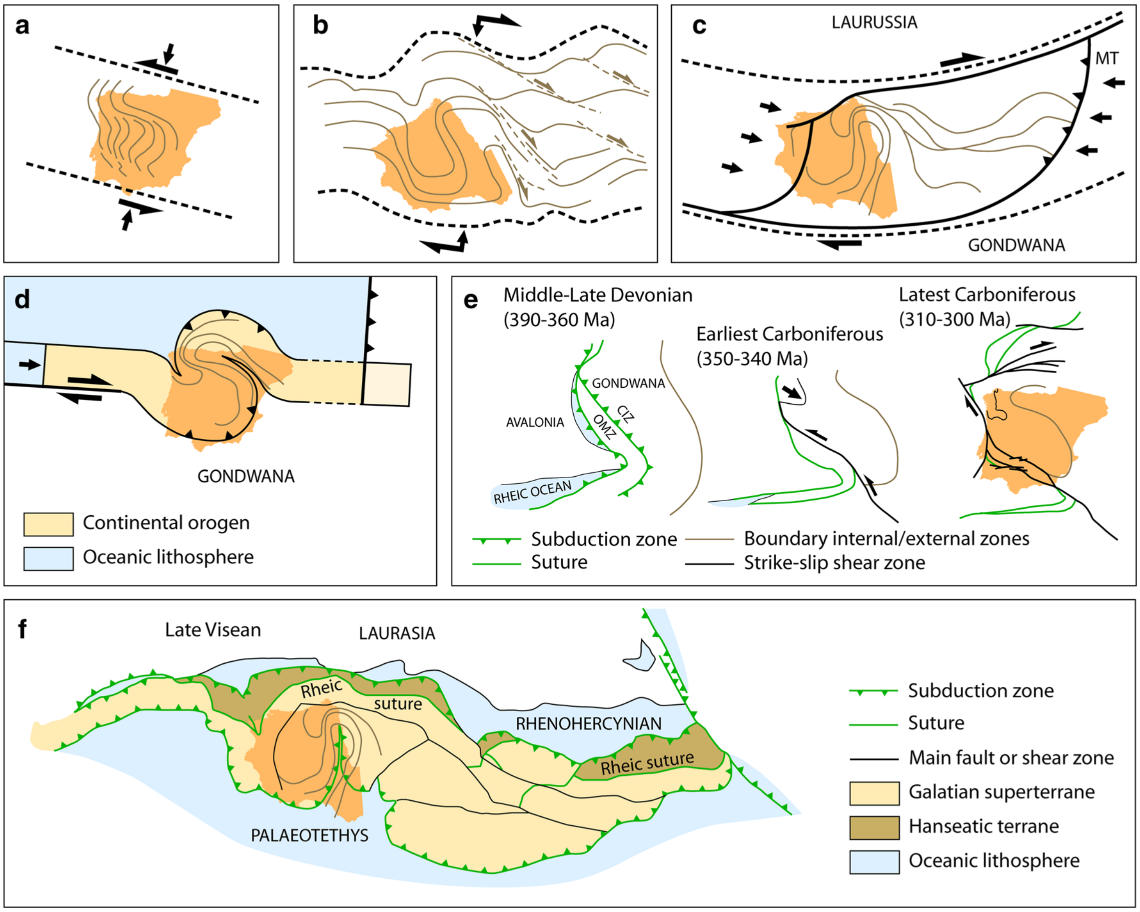

Fig. 6 Mechanisms proposed for the development of the Variscan oroclines. The Iberian Peninsula is outlined as a reference for position and scale. **a** Aerden (2004) envisages sinistral transpression for the coeval formation of the two arcs. **b** Carreras and Druguet (2014) consider dextral transpression, and emphasize gradual crustal-scale strain partitioning with dominantly dextral wrench domains. The arcs would form as back rotation folds develop between ductile shear zones. **c** Martínez Catalán (2011) proposes a compressive bridge inside a dextral shear zone, kinematically equivalent to an intracontinental transform fault. MT Moldanubian thrust. **d** Model of concentric buckling of Johnston et al. (2013) for coupled oroclines modified as to yield a geometry like that of the Iberian oroclines. **e** Model of indentation and left-lateral shearing of Simancas et al. (2013) simplified. *CIZ* Central Iberian Zone, *OMZ* Ossa-Morena Zone. **f** Late Visean stage of the reconstruction of the Variscan domain by Stampfli et al. (2013). The Iberian arcs would have formed after the collision between the Galatian and Hanseatic terranes, and before complete closure of the Palaeotethys and Rhenohercynian oceans

northern margin of Gondwana and alternatively propose parallel translation along the same margin. That model was developed by Johnston et al. (2013) linking secondary oroclines with linear orogens bounded by a continent on one side and by oceanic lithosphere on the other, and ending along strike against a subduction zone. While the oceanic lithosphere is being subducted, the continent is not, and the orogen becomes decoupled through a strike-slip fault, while remaining initially coupled with the oceanic plate. Resistance of the thickened continental crust to be subducted would force it to buckle (Fig. 6d). While this model also involves strike-slip motion, the problem is that the arcs developed following Gondwana-Laurussia collision in the late Carboniferous when no oceanic lithosphere bounded future Iberia (Stampfli et al. 2013). Lateral movements along transform faults are accommodated in convergent plate boundaries, not necessarily oceanic subduction zones. Continental subduction or shortening in the southern Appalachians and the Urals may have absorbed intracontinental dextral transcurrence.

The indentation mechanism has been resumed by Simancas et al. (2013), who interpret the Central Iberian arc as resulting from nucleation around an Avalonian salient, subsequently cut across by the left-lateral shear zones that make it to appear at two different places, Central Iberia and the eastern part of southern Iberia, where its existence is inferred (Fig. 6e). Then, right-lateral shearing would have nucleated the Ibero-Armorican arc and N–S shortening during the latest Carboniferous would have tightened both arcs. The problem here is the age of the

Central Iberian arc, Middle to Late Devonian for Simancas et al. (2013), that is, coeval with the early folds, while the arc bends these structures and the subsequent thrusts.

4.3 Perspectives for the interpretation of the Iberian Variscides

Independently of its origin, the Central Iberian arc provides a new perspective to understand the metamorphic and magmatic evolution of the northwest and central parts of the Iberian Massif. The location of medium- and high-grade Variscan metamorphism in the core of the arc implies that it represents the internal zones of the orogen. The Barrovian gradient developed in the autochthon can be related to crustal thickening by recumbent folding plus thrusting of the allochthonous complexes (Alcock et al. 2009; Rubio Pascual et al. 2013), and would have reached higher P–T conditions just beneath the northwest Iberian allochthon. The medium pressure conditions were followed by a high-temperature and low-pressure event contemporaneous with orogenic collapse and development of gneiss domes (Arenas and Martínez Catalán 2003; Rubio Pascual et al. 2013). Most of the extension predated orocline formation, so that the metamorphic zoning was probably roughly linear. In turn, weakening of the lithosphere by the high temperature reached during thermal relaxation would have facilitated oroclinal buckling (Martínez Catalán et al. 2014).

The zoning established by Bard et al. (1971) for the granitoids in Northwest Iberia (Fig. 4a) cannot be maintained nowadays, but reflects the concentration of syn-kinematic granitoids in the core of the arc. This can in turn be related to radiogenic heat production where the crust had reached its maximum thickness (Fig. 4b). Subsequent closure of the arc would have confined the syn-kinematic granitoids at its core, which may also explain the centrifugal vergences described by López Plaza and Gonzalo (1986).

The post-kinematic granitoids post-dated the Central Iberian arc. However, they are also abundant at and around its core, especially in the Spanish Central System. They represent a late pulse of crustal melting, perhaps related to the peak temperature reached in the lower crust, as found in thermal models by Alcock et al. (2009). Another option is some mantle contribution related to delamination during the closure of the arc. Both possibilities are not exclusive, but their contribution should be evaluated.

An important issue is the hypothesis that the Variscan belt formed by collision of ribbon-like terranes separated from Gondwana by the Palaeotethys (Stampfli and Borel 2002) and from Laurussia by the Rhenohercynian Ocean (von Raumer et al. 2009). Stampfli et al. (2013) interpret the Variscan belt as resulting from collision of two ribbon continents, the Galatian superterrane, separated from Gondwana in the Middle Devonian, and the Hanseatic terrane, separated from Laurasia in the Late Devonian (Fig. 6f).

While Martínez Catalán (2011) and Shaw et al. (2012) have envisaged this possibility as potentially facilitating oroclinal bending, Stampfli et al. (2013) have incorporated the Iberian arcs to a late stage of evolution of their collision between the ribbon continents. However, discrepancies exist in the time of formation of the arcs, late Visean-Bashkirian (330–312 Ma) for Stampfli et al. (2013), a time when the oceanic lithosphere of the Palaeotethys and Rhenohercynian oceans had not been totally closed (Fig. 6f). However, the age of the Iberian arcs has been bracketed between 315 and 299 Ma (Weil 2006; Weil et al. 2010, 2013; Pastor-Galán et al. 2011; Martínez Catalán 2011, 2012), when the oceanic lithosphere had disappeared, and the Gondwana-Laurussia collision had been completed in the European Variscides. This lends support to the intracontinental formation of the oroclines in the strip of Pangea weakened by thermal relaxation of the Variscan belt. But the hypothesis of a weakened intracontinental zone should be tested against the ribbon continent option, a matter of investigation that may contribute to understand the formation of oroclines.

5 Conclusions

The "Castilian bend" proposed by Rudolf Staub in 1926 is actually an orocline now known as the Central Iberian arc. Its core is not formed by an Archaean block, but represents the internal zones of the Variscan belt, those preserving a Palaeozoic suture witnessing the Variscan collision, and the ones having registered the highest pressures and temperatures and more voluminous Variscan plutonism. The orocline was included in sketches of some classical books, but once rejected by Franz Lotze shortly after having been proposed, it remained practically forgotten for more than half a century. However, some hints of its existence can be found in a few papers of the seventies and eighties of the 20th century, and in a report of the Instituto Geológico y Minero de España. The report benefited from geophysical data, which actually represent one of the main supports for the existence of the orocline.

The 21st century has seen the rediscovery of the arc and papers describing its geometry, based on structural, geophysical, and sedimentary criteria, have been published. Also, its meaning in the frame of the Variscan belt is being discussed, and different hypothesis have been proposed for its origin. Among them, those assigning an important role to transcurrent movemet prevail, but indentation remains a real possibility.

The Central Iberian arc explains the structural occurrence of the northwest Iberian allochthons and the distribution of metamorphism and granitoids, but numerous unknowns exist. These are related to the mechanics of oroclinal folding in Iberia, the relation with the rest of the Variscan belt in Europe and the Appalachians, and the potential influence of mantle dynamics in its development. To solve them, palinspastic reconstructions based on palaeomagnetism, improved knowledge of the oceans involved, interpretation of the Variscan magmatic record, and restoration of the finite strain associated with orocline formation would be needed.

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