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Late/Post Variscan Orocline Formation and Widespread Magmatism

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Abstract

The Paleozoic geology of Iberia is dominated by the tectonics of the Variscan orogeny and its aftermath. This defining geologic event was the result of large-scale collision that involved amalgamation of multiple continents and micro-continents, the closure of oceanic basins and eventual orogenic collapse, and finally modification and oroclinal bending during the waning stages of Pangea amalgamation. Existing data from the western Variscan orogen, suggests oroclinal bending of an originally near-linear convergent margin during the last stages of Variscan deformation occurred in the late Paleozoic. Earlier closure of the Rheic Ocean resulted in E-W shortening (in present-day coordinates) in the Carboniferous, producing a N-S trending, east verging belt. Subsequent deformation near the Carboniferous-Permian boundary resulted in oroclinal bending. This late-stage orogenic event remains an enigmatic part of Iberia's Paleozoic history.

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14.1 Introduction

The formation of the supercontinent Pangea, one of the cornerstones of geology and plate tectonics, has a complex history that is preserved in the geologic record of the Paleozoic Era. Although, the kinematics and mechanisms responsible for its amalgamation are not fully understood and still debated (e.g. Domeier et al. 2012; Stampfli et al. 2013; Domeier and Torsvik 2014; Gallo et al. 2017), the general consensus is that the final amalgamation of Pangea occurred during the late Paleozoic. At the supercontinents center was the sinuous Variscan–Alleghanian orogeny, which formed from the oblique collision between Gondwana, Laurussia, and several microplates, and the closure of at least two and probably four oceans (Fig. 14.1) (Winchester et al. 2002; Martínez-Catalán et al. 1997, 2007; Matte 2001; Franke et al. 2017). This collisional belt is a complex continental-scale orogen (1000 km wide and 8000 km long) that formed through a series of protracted tectonic episodes from initial convergence at about 420 Ma to final collision at about 310 Ma (e.g., Franke et al. 2005; Martínez-Catalán et al. 2007; Diez-Fernández et al. 2016).

Though not the focus of this section, a brief review of the Variscan system in Iberia is given to establish the existing geologic framework of the region prior to the late-Variscan modification that produced oroclinal rotations, and resulted in coeval widespread magmatism. The European Variscan autochthon is generally thought to be of Gondwanan affinity and consists of an early Paleozoic passive margin sequence constructed unconformably on Proterozoic crust that itself was deformed during Cadomian (late Ediacaran) orogenesis (e.g. Abati et al. 2010; Pastor-Galán et al. 2013a; Shaw et al. 2014; Gutiérrez-Alonso et al. 2015). The allochthonous terranes of the Variscan orogen include continental terranes of peri-Gondwanan affinity and oceanic terranes containing ophiolites, arc rocks and associated accretionary complexes. The Rheic Ocean is the paleogeographic realm that opened during the early Paleozoic drift of peri-Gondwanan terranes

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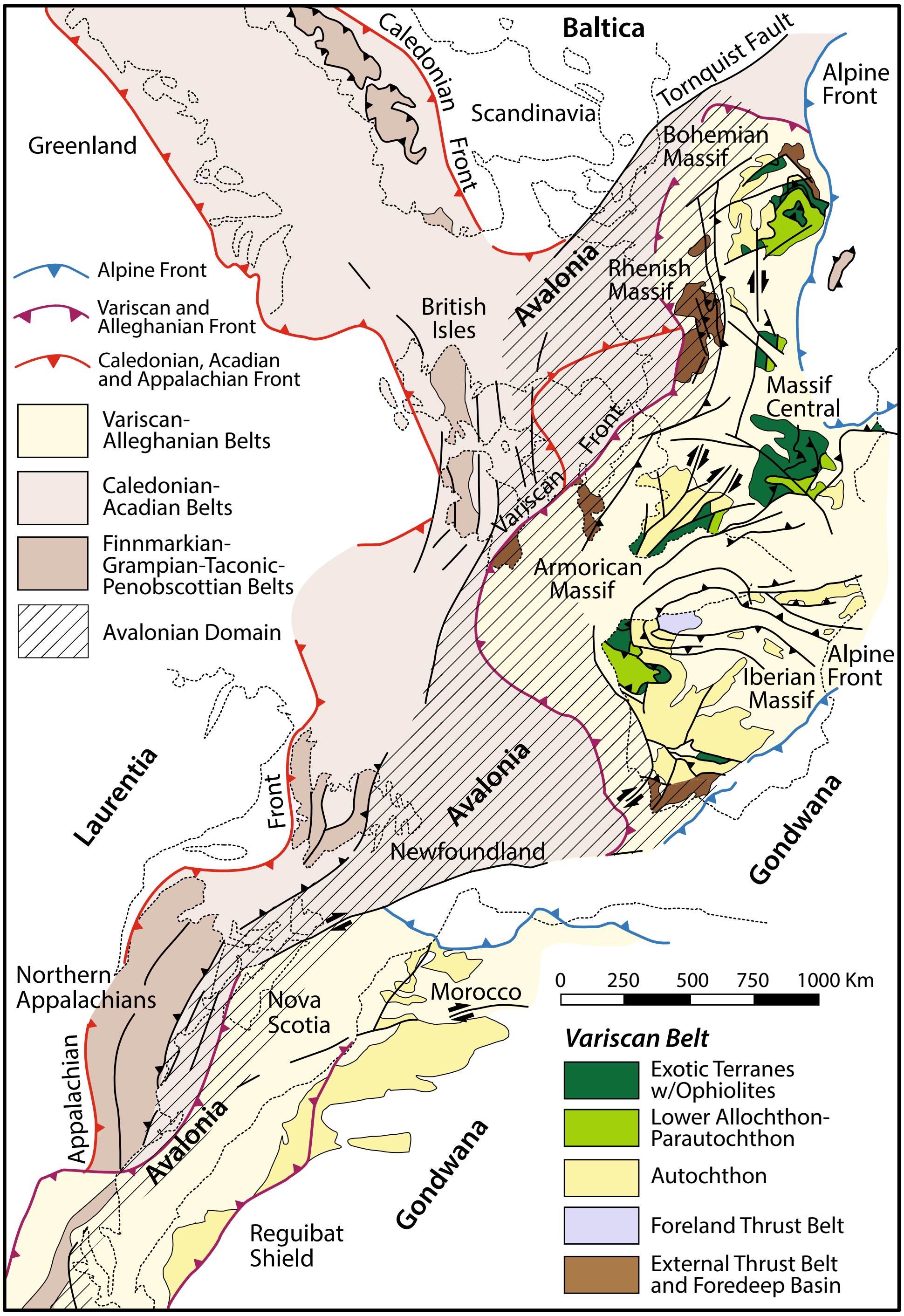

Fig. 14.1 Tectonostratigraphic and paleogeographic map of the Caledonide-Appalachian-Variscan orogenic system (modified after Martínez-Catalán et al. 2009)

(e.g., Avalonia-Meguma) from the northern margin of West Gondwana. Opening of the Rheic Ocean produced passive margin sedimentation along the north-facing Variscan margin of Gondwana. The boundary between the Variscan autochthon and peri-Gondwanan allochthon marks the suture of the Rheic Ocean (e.g., Murphy et al. 2006; Nance and Linnemann 2008; Nance et al. 2010, 2012). Though consensus exists on the importance of the Rheic Ocean in the tectonic evolution of the Variscan orogeny, there remains debate on the existence of additional basins that may have been involved in generating the tectonostratigraphic framework observed today (e.g., Lardeaux 2014; von Raumer

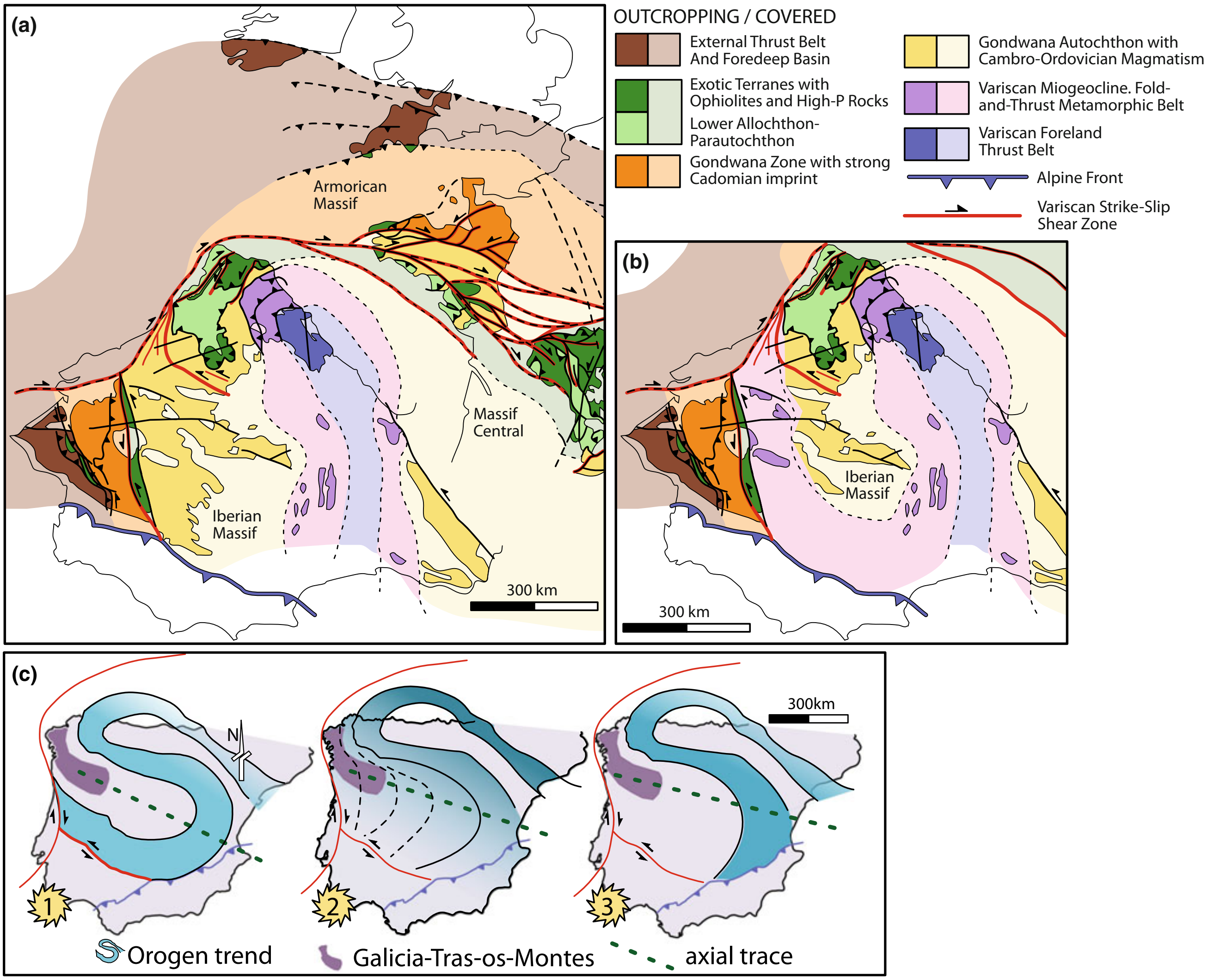

Fig. 14.2 **a** A classic interpretation of the tectonostratigraphic zonation of the Variscan orogen in southwestern Europe (modified from Franke 1989; Martínez-Catalán et al. 2007). **b** Alternative interpretation with Iberian oroclines after Shaw et al. (2015). **c** Alternative geometries of the proposed double orocline of Iberia

et al. 2009, 2013; Stampfli et al. 2002; Franke et al. 2000, 2017; Tait et al. 2000; Matte 1986, 1991, 2001).

The Iberian Massif preserves the most complete exposure of the Variscan autochthon (Fig. 14.2) (e.g., Du Toit 1937; Dvorak 1983; Martínez Catalán 2011). The autochthon has historically been divided into a series of tectonostratigraphic domains based on their pre-Variscan stratigraphy and Variscan deformational style. From east to west, in present-day coordinates, is a thin-skinned foreland fold and thrust belt, and external and internal hinterland domains that become progressively more deformed and metamorphosed toward the shallowly emplaced ophiolites to the west (Fig. 14.2) (e.g., Martínez-Catalán et al. 2007). Sedimentological, geochemical, and paleontological constraints indicate that during the early Paleozoic, the foreland and hinterland autochthonous domains were positioned as a north-facing passive margin off the north margin of West Gondwana (e.g., Shaw and Johnston 2016a).

Late, to post-orogenic modification of the Europe Variscan Belt was ultimately responsible for its characteristic sinuous shape that today traces at least one, and possibly four complete arcs (arc is used throughout this section as a geometric description of a curved orogenic system, with no implications on genesis of the curvature or magmatism) from Poland to Brittany, and then across the Bay of Biscay (Cantabrian Sea) into Iberia, where the belt is truncated by the Betic Alpine front in southern Spain (Fig. 14.2). Today the Variscan of Iberia is interpreted to define a sinuous "S" shape trend that has stimulated debate for more than a century (Fig. 14.2; e.g. Suess 1885; Staub 1926). The Cantabrian Orocline (orocline is used throughout this paper as a kinematic term that describes the secondary rotation of

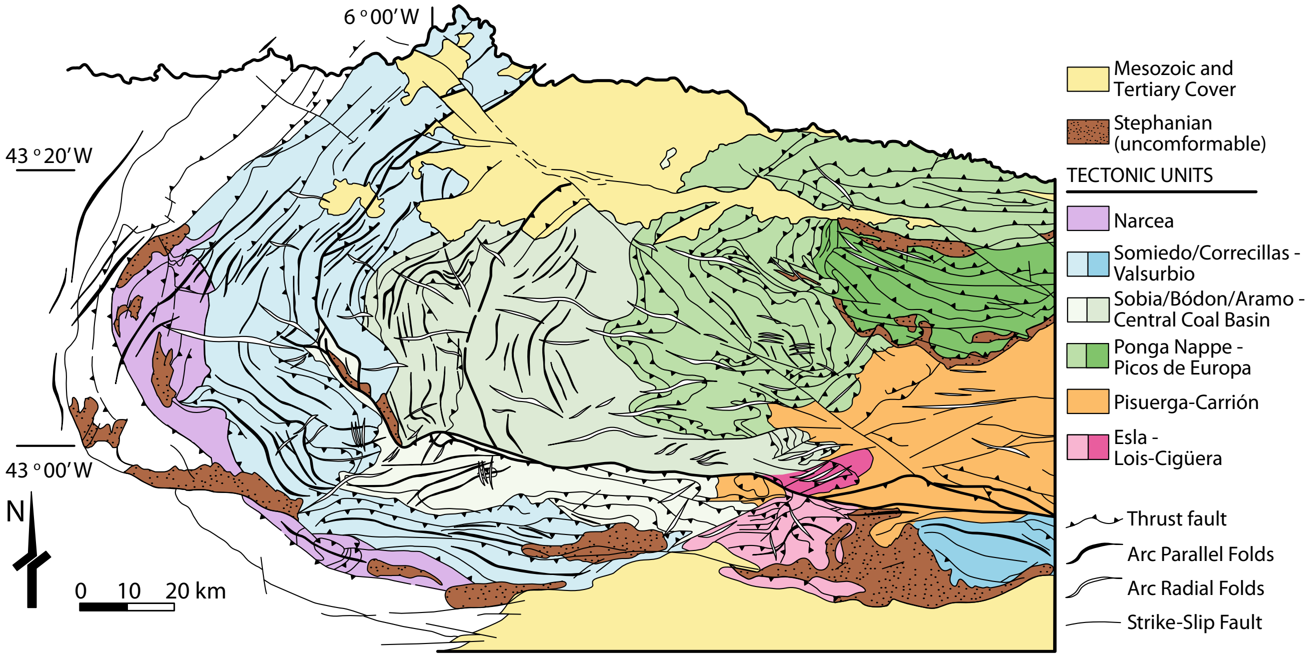

Fig. 14.3 Simplified structure/tectonic map of the Cantabrian Orocline, highlighting the geometry of major thrusts and the orientation of arc-parallel and arc-perpendicular folds. Tectonic unit divisions modified from Alonso et al. (2009)

an originally linear orogenic system—as originally defined by Carey 1955) is the name used herein to describe the concave to the east (forelandward) curvature located in northwest Spain and northern Portugal (Fig. 14.3) (a.k.a. Cantabrian Arc and Cantabria-Asturias Arc). The Central Iberian Arc, which is less conspicuous, is located in central Spain and is characterized by a convex to the west curvature (Fig. 14.2) (a.k.a. Central Iberian Curve, Central Iberian Orocline). Whereas the kinematics of the Cantabrian Orocline is well established, the shape, kinematic and tectonic implications of the Central Iberian Arc are debated (Fig. 14.2c).

14.2 The Cantabrian Orocline: Geometry and Kinematics

The Cantabrian Orocline is one of the first curved orogens ever described in the literature. Referred to as the "Asturian knee" (Suess 1885), the tectonic bend was recognized by the change in structural trend of thrusts and fold axes that when mapped, trace an arc curvature of up to 180° that opens towards the foreland (Fig. 14.3). At its full extent, the Cantabrian Orocline is a first order vertical axis fold that refolds pre-existing Variscan structures. In the core of the orocline are an assortment of structures that record non-coaxial strain, which produced complex interference folds and rotated thrust sheets (e.g. Julivert and Marcos 1973; Aller and Gallastegui 1995; Weil 2006; Pastor-Galán et al. 2012; Shaw et al. 2016; Del Greco et al. 2016).

Many authors have studied the Cantabrian Orocline over the past few decades, especially within its core, the Cantabrian Zone (Fig. 14.3). This body of work resulted in a variety of hypotheses for how, when, and why the orocline formed. The Cantabrian Zone, representing the Gondwanan foreland fold-and-thrust belt of the Variscan Orogen, is characterized by tectonic transport towards the core of the orocline, i.e., the orocline has a contractional core, where low finite strain values and locally developed cleavage occur (Pérez-Estaún et al. 1988; Gutiérrez-Alonso 1996; Pastor-Galán et al. 2009). Illite crystallinity and conodont color alteration indexes are consistent with diagenetic conditions to very low-grade metamorphism in this region (e.g. Gutiérrez-Alonso and Nieto 1996; Abad et al. 2003; Colmenero et al. 2008, Pastor-Galán et al. 2013b, Garcia-Lopez et al. 2013).

A wealth of paleomagnetic (e.g. Hirt et al. 1992; Parés et al. 1994; Stewart 1995; van der Voo et al. 1997; Weil 2006; Weil et al. 2000, 2001, 2010), structural (e.g. Julivert and Marcos 1973; Pérez-Estaún 1988; Gutiérrez-Alonso 1992; Kollmeier et al. 2000; Pastor-Galán et al. 2011, 2012, 2014; Shaw et al. 2016) and geochronological data (e.g., Gutiérrez-Alonso et al. 2015) support the hypothesis that the Cantabrian Orocline formed due to secondary vertical axis rotation subsequent to the main collisional phases of the Variscan orogen (meaning younger than ca. 310 Ma).

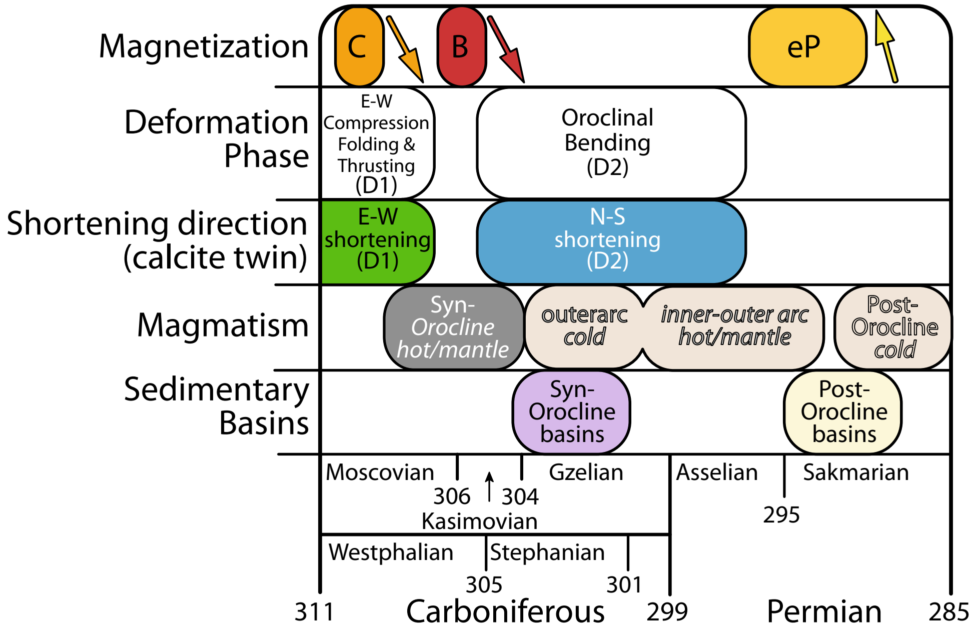

Fig. 14.4 Proposed timeline for the temporal relationship between the successive magnetizations recorded in the Cantabrian Orocline and their relationship to the two main phases of oroclinal formation, the acquisition of twin strains (and associated stresses) during deformation, the age of various magmatic pulses, and the age of sedimentary basins. Modified from the review article of Weil et al. (2013a, b)

Importantly, the documented rotations, which are recorded in rock units throughout the foreland and hinterland of the Iberian Variscan system, occurred over a relatively short interval of time from 310 to 295 Ma (Fig. 14.4) (see summary at Gutiérrez-Alonso et al. 2012; Weil et al. 2013a, b), and thus are truly secondary and post-orogenic with respect to Variscan deformation.

14.2.1 A Forgotten Curvature: Geometry and Kinematics of the Central Iberia Arc

Although described as early as 1926 by Staub (see Martínez-Catalán et al. (2015) for a historical perspective), the shape, kinematic and tectonic implications of the Central Iberian Arc remained overlooked for decades; thus, many models of orocline development for the Cantabrian Orocline completely ignored the influence on and of its potential southern counterpart (Fig. 14.2b). Based on his observations of the structural trend of folds and inclusions in garnets around the putative hinge of the Central Iberian Arc, Aerden (2004) reignited the hypothesis of their being an additional Central Iberian Arc and suggested that it was secondary in nature. Since then, multiple authors have tried to unravel its geometry and kinematics with conflicting results. The observations used in support of the Central Iberian curved geometry are: (i) paleocurrents recorded in Ordovician quartzites (Shaw et al. 2012); (ii) structural trend of folds and inclusions in garnets (Aerden 2004) and (iii) aeromagnetic anomalies and fold trends (Martínez-Catalán 2012). Based on these arguments, three geometries have been proposed (Fig. 14.2c) that have two features in common: (1) the curvature runs parallel to the Central Iberian Zone, located in the center-west of Iberia and (2) the Galicia-Tras-os-Montes Zone occurs in the core of the curve.

Paleomagnetic results from the Central Iberian Arc published by Pastor-Galán et al. (2015a, 2016, 2018), suggest a lack of secondary rotation on the southern limb of the arc that were penecontemporaneous with rotations recorded in the limbs of the Cantabrian Orocline (Fig. 14.5). However, the timing constraints provided by these results only established that no relative rotation occurred younger than ca. 318 Ma. Consequently, the available paleomagnetic data from the Central Iberian Arc neither definitively supports or refute a secondary nature for the arc, but does require that if it is secondary, and thus an orocline, it had to have occurred prior to 318 Ma, and is thus diachronous with the Cantabrian Orocline (Fig. 14.5). This ambiguity makes the kinematic nature of the Central Iberian Arc one of the most important outstanding questions in terms of the Variscan of Iberia, and the broader tectonics and paleogeography of Western Europe during the late-stages of Pangea amalgamation.

Coupled oroclines, like the Cantabrian and Central Iberian oroclines, are not uncommon, and have been documented in Mesozoic, Paleozoic and Precambrian orogens. Examples include the coupled North Alaskan and Kulukbuk Hills oroclines of the Cordilleran orogen of Alaska, the Carpathian and Balkan oroclines of the Eastern Alpine belt, and the Bothnian oroclines of the Svecofennian orogen of Baltica (Shaw and Johnston 2016a, b; Lahtinen et al. 2014). A model of coupled orocline development as a result of concentric buckling of a pre-existing linear orogen (Johnston et al. 2013) involves the development of an initial concentric buckle whose axial surface is perpendicular to the strike of

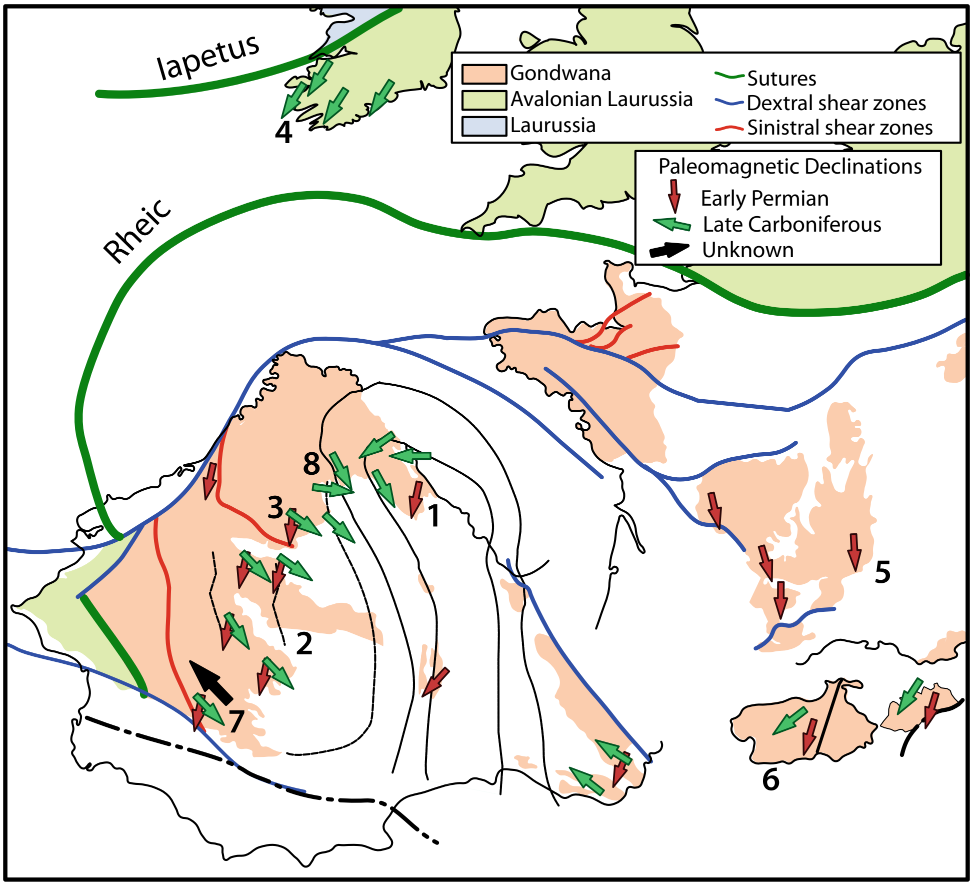

Fig. 14.5 Compilation of Pensylvannian and Early Permian paleomagnetic declinations in Iberia, France and Ireland (see Weil et al. 2013a, b [1]; Pastor-Galán et al. 2015a [2]; 2016 [3]; 2015b [4]; Edel et al. 2014 [5] and 2015 [6]; Parés and van der Voo 1992 [7]; Fernández-Lozano et al. 2016 [8]). Note the absence of Pensylvannian clock-wise rotations around the Central Iberian curve, however a declination of unknown age might indicate an earlier formation of the Central Iberian orocline (arrow in black [7])

the deforming orogen. Continued orogen-parallel shortening is then taken up by continued rotation of the initial buckle. A 90° rotation of the initial buckle gives rise to two coupled oroclines whose axial surfaces strike parallel to the regional strike of the orogen. Diachroneity of the two coupled oroclines is a prediction of this model. The paleomagnetic data provided by Pastor-Galán et al. (2015a, 2016) indicates that the Central Iberian arc predates the Cantabrian arc. If correct, the implication of the concentric buckling model is that the Central Iberian arc developed first by concentric buckling of the Variscan orogen to the south (present-day coordinates) and that continued orogen-parallel shortening was subsequently taken up by counter-clockwise rotation of the Central Iberian orocline, giving rise to the Cantabrian orocline. Further paleomagnetic and structural data are required to test this two-stage coupled orocline model.

14.3 Magmatism

Iberia preserves an impressive record of magmatic pulses that flared up during the Late Paleozoic, including 350–330 Ma (orogen building); 325–315 Ma (orogen collapse) and 310–285 (Late orogenic) (Fig. 14.6) (Fernández-Suárez et al. 2000). Late-orogenic magmatism comprises intrusive and volcanic rocks emplaced from 310 to 285 Ma, which are penecontemporaneous with, and slightly post-date formation of the Cantabrian Orocline. The late-orogenic magmatic record consists of mantle and crustal derived melts that show systematic changes in their age, spatial distribution, petrology, and geochemistry, and include foreland magmatism (a rarity in classic foreland systems) in the core of the Cantabrian Orocline (Gutiérrez-Alonso et al. 2011a, b).

Available geochronological data indicate that late orogenic magmatism (310–285 Ma) progressively youngs towards the core of the Cantabrian Orocline (Fig. 14.7) (Fernández-Suárez et al. 2000; Gutiérrez-Alonso et al. 2011a, b). In the outer regions of the Cantabrian Orocline, scarce but significant mantle and lower crustal derived mafic melts intruded from 310 to 305 Ma, which were followed by intrusion of felsic, crustal derived magmas between 305 and 295 Ma. Within the inner orocline (the Cantabrian Zone), magmatism did not begin until 300 Ma and did not end until 285 Ma (Fig. 14.7b). Similar to the outer orocline, magmatism began with the intrusion of mantle and lower crust-derived mafic rocks and granitoids, and widespread volcanism that continued until 292 Ma (Gutiérrez-Alonso et al. 2011b). Subsequently, felsic, crustal-derived

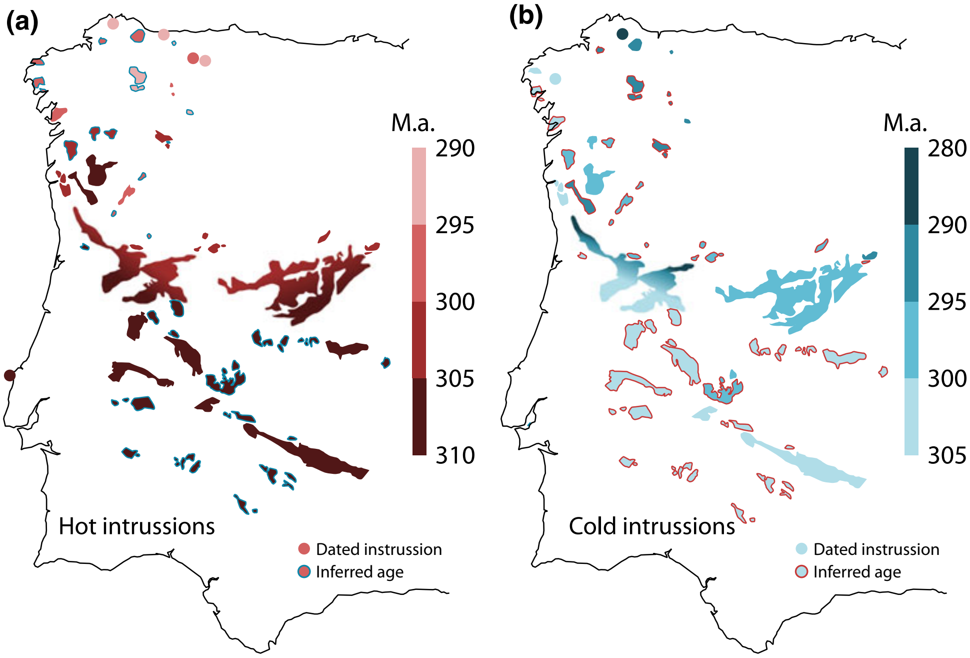

Fig. 14.6 Map of western Iberia showing spatial distribution of Late Variscan magmatism. **a** Distribution and time of emplacement of mafic rocks, granodiorites and monzogranites ("hot"). **b** Distribution and time of emplacement of leucogranites ("cold"). After Gutierrez-Alonso et al. (2011a, b); Orejana et al. (2012)

leucogranite magmatism continued for another 7 m.y. (Gutiérrez-Alonso et al. 2011b).

Sm/Nd isotopes from mantle-derived rocks revealed that the mantle lithosphere in NW Iberia was emplaced, or strongly metasomatized, at ca. 1.0 Ga, while post-Variscan mantle-derived magmatic rocks yield neodymium model ages (TDM) of ca. 300 Ma (Fig. 14.7c) (Gutiérrez-Alonso et al. 2011b). The newer model age is roughly coeval with the formation of the Cantabrian Orocline and the late Variscan magmatic pulse and implies a lithospheric-scale readjustment and replacement during oroclinal development.

14.4 Late Variscan Tectonic Models

The large amount of work over the past two decades on the kinematics of the Cantabrian (see reviews of Weil et al. 2013a, b; Johnston et al. 2013) and Central Iberian arcs (e.g. Martínez-Catalán, et al. 2015; Shaw and Johnston 2016a, b; Pastor-Galán et al. 2016; 2017; da Silva et al. 2017) inspired a revitalization of published tectonic models for the mechanisms that formed these first-order geologic structures. The kinematic restrictions imposed by paleomagnetism and structural geology established that formation of the Cantabrian Orocline occurred within 15–20 million year time window from late Carboniferous to the earliest Permian (Fig. 14.4) (e.g., Merino-Tomé et al. 2009; Weil et al. 2010; Pastor-Galán et al. 2011, 2014; Gutiérrez-Alonso et al. 2015; Shaw et al. 2016). Consequently, any viable tectonic model must conform to the kinematic framework of secondary rotation of the northern and southern limbs of the Cantabrian Orocline during a period of less than 20 m.y. around the Carboniferous-Permian boundary. However, the still ambiguous nature on the geometry and kinematics of the Central Iberian arc limits any proposed tectonic scenario and therefore adds uncertainty to all the proposed current models.

Like many events in ancient Earth history, authors working on the Late Variscan have proposed a number of competing non-unique explanations that are based on, and limited by, a particular set of published observations (Fig. 14.8). Based on our current understanding of late Variscan kinematics (see Weil et al. 2013a, b; Dias et al. 2016 for recent reviews), the most common hypotheses for the Variscan orocline(s) in Iberia involve: (1) a collision between irregular coastlines including promontory–salient pairs, in which indentation of blocks and/or deformation of embayments initiated the observed curvature(s) (e.g., Lefort 1979; Dias and Ribeiro 1995; Simancas et al. 2005); (2) the buckling of a ribbon-like continent that requires at least one side of the ancient landmass to be bound by oceanic lithosphere (e.g., Johnston et al. 2013; Shaw and Johnston 2016b); (3) a stress-field change due to paleogeographic position of Iberia in the core of the Pangea supercontinent and at the apex of the Tethyan realm (e.g., Gutiérrez-Alonso et al. 2008); (4) regional rotation of existing tectonostratigraphic zones due to continental-scale shear faulting associated with oblique shortening and/or transpression (e.g. Brun and Burg 1982; Martínez-Catalán 2011); and (5) a change in the regional stress field by 90°, which causes non-coaxial deformation and vertical-axis rotation of initially linear features, generally interpreted as lithospheric-scale buckling.

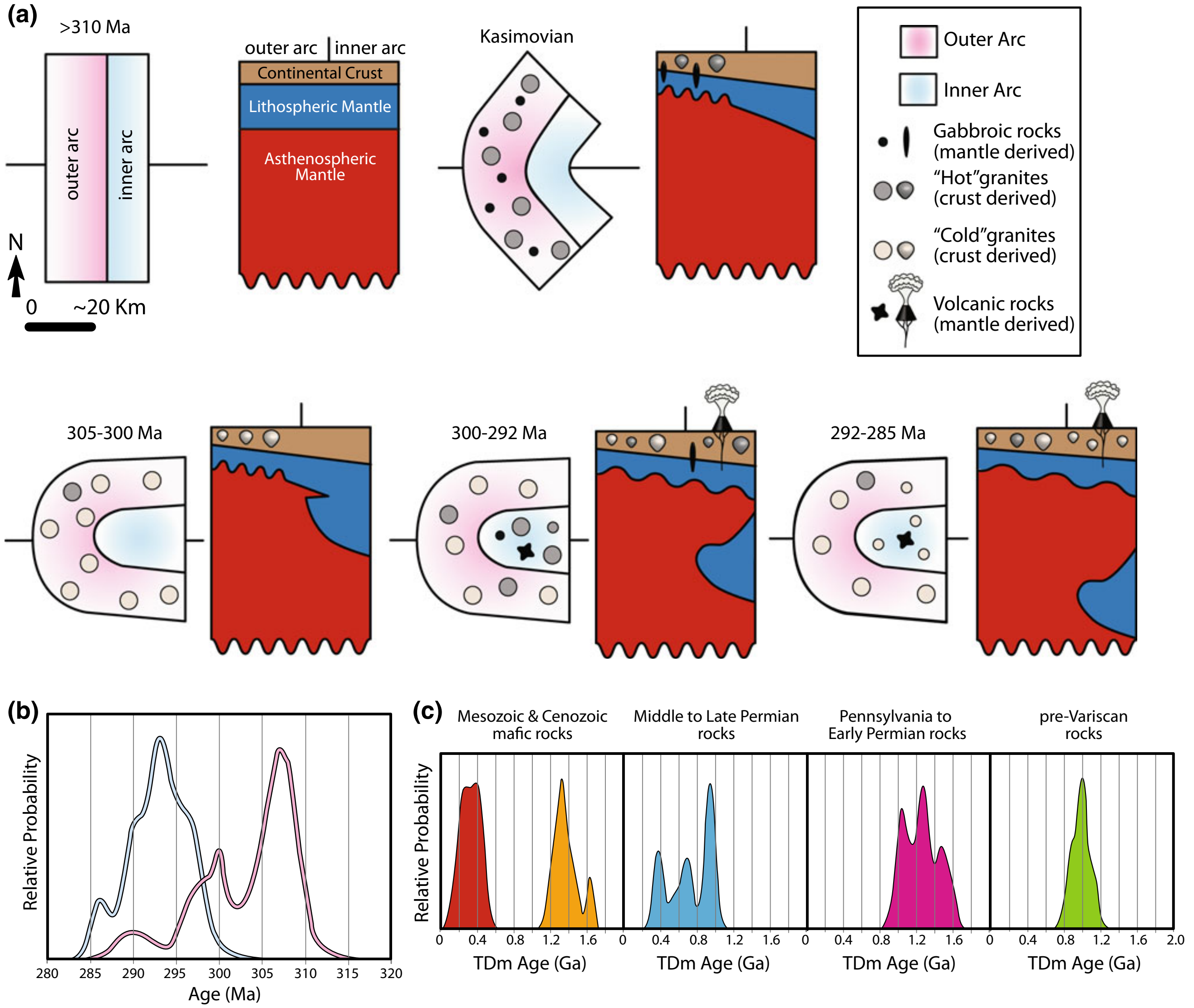

Fig. 14.7 Cartoon sketches summarizing the episodes of magmatism during formation of the Cantabrian Orocline. Outer (inner) arc region highlighted in pink (blue). **a** Plan view and profile view models for lithospheric structure of inner and outer arc during oroclinal development. **b** Probability age distributions for magmatic rocks from the inner (blue) and outer (pink) arc regions. Note the general younging trend of magmatic ages from outer to inner arc during oroclinal buckling and related lithospheric delamination. **c** Model εNd age probability plots grouped as: Mesozoic and Cenozoic mafic rocks, Middle to Late Permian rocks, Pennsylvanian to Early Permian samples, and pre-Variscan samples. Data and schematic cartoons taken and modified Gutiérrez-Alonso (2011a, b)

None of these models are necessarily mutually exclusive, and the truth may lie at the intersection of two or more of these scenarios. These models are discussed below with an emphasis on recent publications. This discussion is followed by a review of the nature and number of Variscan aged oroclines in Iberia.

Models that call upon the modification of a linear Variscan margin by the impingement of a rigid block began with the promontory hypothesis of Lorenz (1976) and Lorenz and Nicholls (1984). These models focused on the final collision of Pangea and the collapsing of the recently deformed and weakened European Variscan realm between the irregular margins of the stronger Laurussia and Gondwana plates (Fig. 14.8a). Thus, the strong rheological contrast within the colliding collage caused progressive rotation and formation of the Iberian orocline(s). An alternative model was later proposed by Matte and Burg (1981) and modified by Matte (1991), in which a rigid block migrated from the east (in present-day coordinates) and indented into the European Variscan belt causing opposite shear sense on either arm of the centripetal vergent bend (Fig. 14.8b). The more recent iteration for this model, which has indentation occurring in two stages, comes from Dias and Ribeiro (1995) (Fig. 14.8 c). Invariably, the hypothesized indentor has a Gondwana affinity basement, and was likely a promontory off the northern margin of Gondwana (e.g., Lefort and Van der Voo 1981; Lefort 1989; Quesada et al. 1991) (Fig. 14.8d). Şengör (2013) brought back a modified version of Matte's westward indentor, linking deformation in the distal Pyrenean realm of the Variscan to the development of the Cantabrian Orocline. In his model, oroclinal bending is related to a westward moving strut, which caused thin-skinned deformation and associated shear faulting, and is explicitly not lithospheric-scale in nature. Simancas et al. (2013) expands on earlier indentor models to include the formation of the Central Iberian arc, which they argue nucleated around an Avalonian salient that was subsequently modified by shear faulting (Fig. 14.8e). In addition, models related with roll-back curvature caused by a post-Variscan subduction zone located to the south of the Cantabrian orocline have been proposed (Pereira et al. 2015).

The indentor model faces several challenges including the absence of an identified indentor, the difficulty in reconciling the extreme tightening observed in the inner Cantabrian Orocline with the expected radial deformation (e.g. Weil 2006; Merino-Tomé et al. 2009; Reiter et al. 2011); and importantly, the fact that vertical-axis rotations happened after larger-scale regional tectonic convergence (e.g. Dallmeyer et al. 1997; Ribeiro et al. 2007; Weil et al. 2000, 2010, 2013a, b). Consequently, the most recent models have

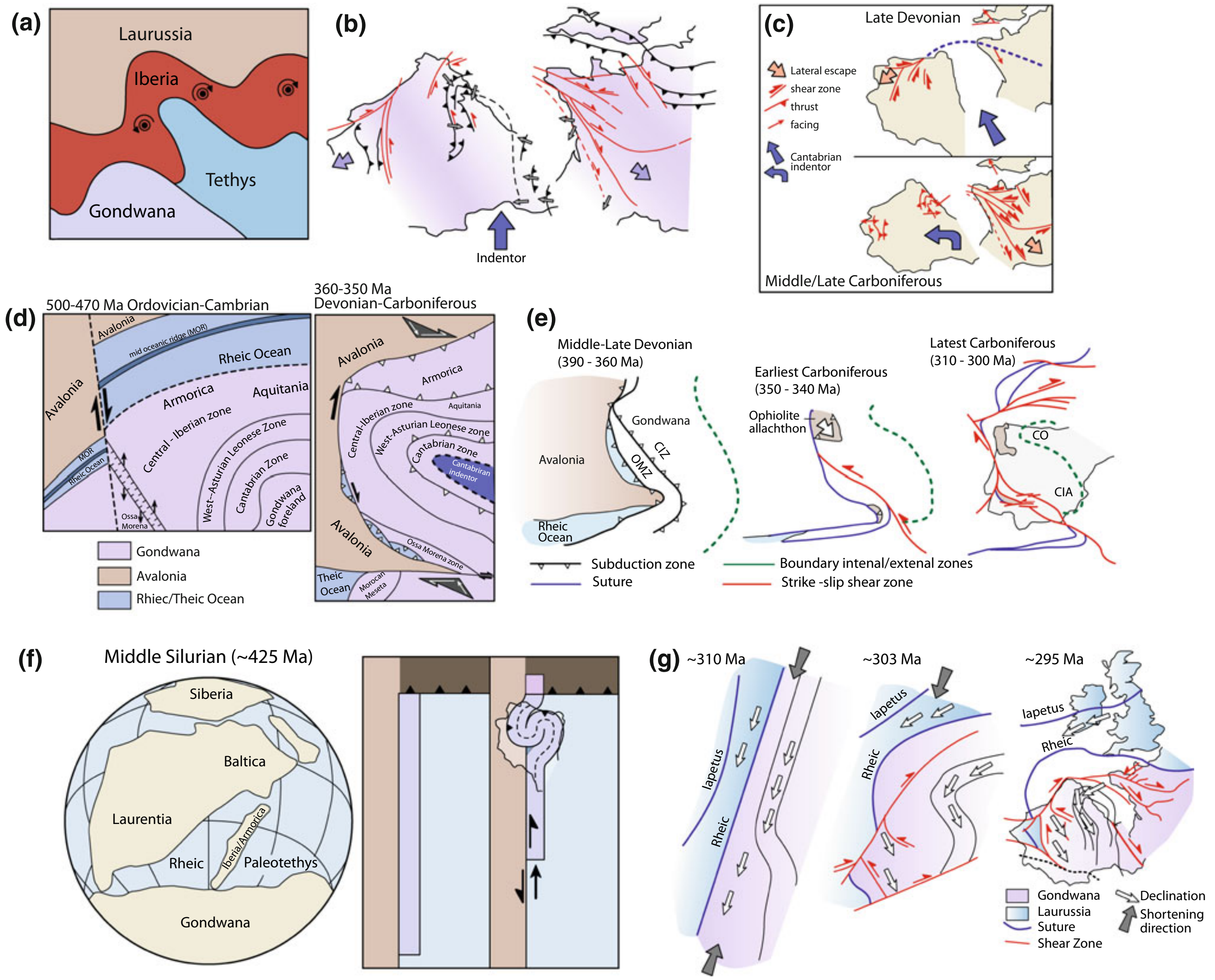

Fig. 14.8 Various models of oroclinal formation. **a** Indentor model after Lorenz and Nicholls (1984). **b** Indentor mode with fault kinematics from Matte and Ribeiro (1975) and Matte (1991). **c** Two-stage indentor model after Dias and Ribeiro (1995). **d** Gondwana promontory indentor model after Ribeiro (2007). **e** Kinematic model with indentation and left-lateral shearing after Simancas et al. (2013). **f** Simplified ribbon continent model after Johnston et al. (2013) and Shaw and Johnston (2016a, b). **g** Stress-Field rotation and shear zone kinematic model of Pastor-Galán et al. (2015b). **h** Pangea self-subduction model from Gutiérrez-Alonso et al. (2008). **i** Dextral mega-shear model from Martínez-Catalán (2014). **j** North Iberian mega-shear model after Martínez-García (2013). **k** Oroclinal induced lithospheric delamination model after Gutiérrez-Alonso et al. (2004, 2012)

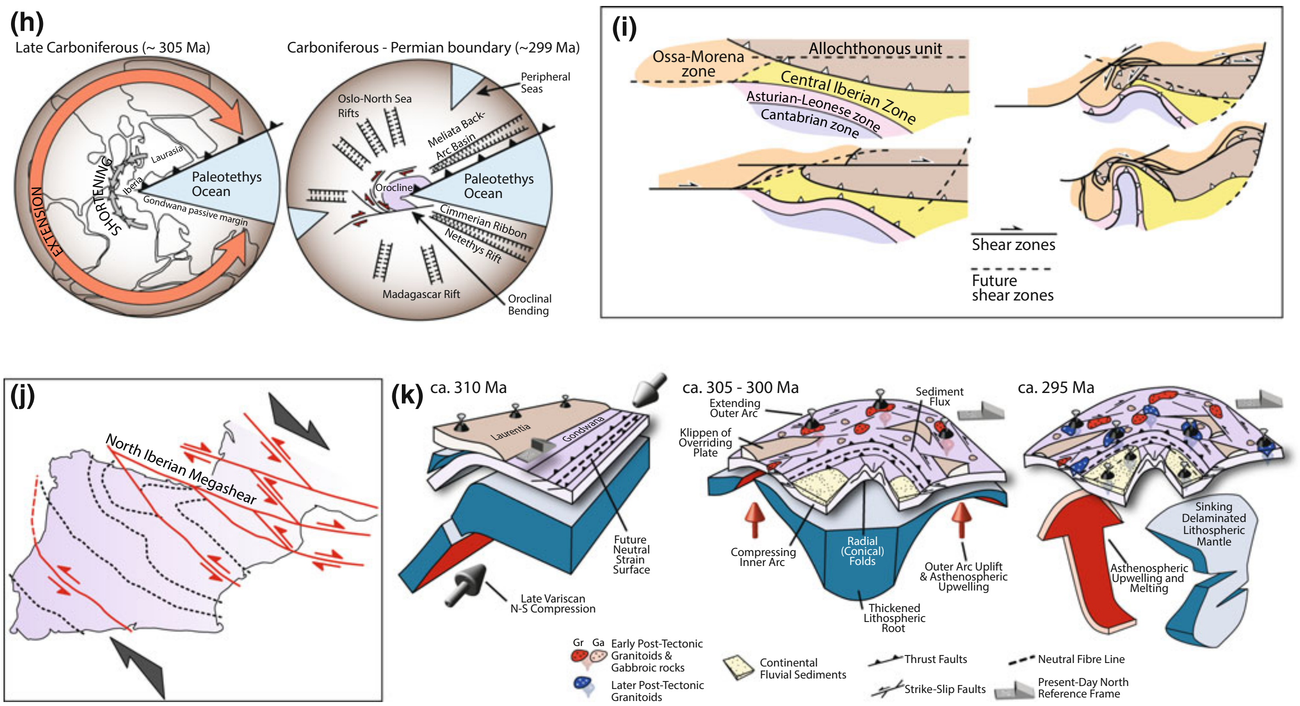

Fig. 14.8 (continued)

been formulated with an effort in reconciling the indentor model with late-stage oroclinal formation by integrating an early phase of indentation with later oroclinal bending and arc tightening. To this end, Dias et al. (2016) argues that the irregular shape of the Laurussian margin induced rotation in Iberia by translating the Cantabrian basement to the east, forming a tight fold in the hinge area of the arc, while the more external limbs of the belt in Central Iberia and north into Brittany underwent only minor rotation. These more distal regions of the arc are therefore not part of the established oroclinal system, but instead represent the trends of two mostly independent tectonic zones that were at a high angle to one another at the end of Variscan tectonics. However, recent paleomagnetic data from Ireland does not support the proposed trend for the northern arm of this system in the Late Paleozoic (Pastor-Galán et al. 2015b). Murphy et al. (2016) further hypothesized a two-stage tectonic model in which the first phase initiated with the collision of a large promontory into Iberia in the Devonian. This collision resulted in a relatively straight inner Cantabrian zone and an outer zone that accommodated indentation by sinistral and dextral motion along shear zones on either side of an impinging promontory. The main tectonostratigraphic zones were subsequently bent due to a change in the stress field associated with regional heterogeneities in small ocean tracks preserved in the reentrants and promontories produced during the earlier collision.

Although indentor/promontory models vary in their details, they inevitably place the Variscan of Iberia in the continental interior of an amalgamating Pangea. An alternative set of models argue that the Variscan of Iberia was initially a ribbon continent that rifted away from the northern margin of Gondwana leaving a new tract of oceanic lithosphere on its eastern flank (Fig. 14.8f) (Johnston et al. 2013; Shaw et al. 2014, 2015; Shaw and Johnston 2016a, b). In this scenario both the Cantabrian Orocline and the Central Iberian Arc are secondary curves that result in the buckling of an initially ~2100 km long linear orogen. In order to account for the present-day arc curvature of the coupled bends, roughly 1100 km of shortening is required. This massive shortening is argued to have been accommodated by a subduction-related driving mechanism that produced orogen-parallel shortening (Johnston et al. 2013). This model results in a 90° change in the shortening field from an early east-west (in present-day coordinates) event that resulted in establishment of the early longitudinal folds and faults that define the main structural grain of Variscan deformation in Iberia, to north-south, causing the ribbon continent to buckle between Gondwana and Laurussia. Recently Fernández-Lozano et al. (2016) published new paleomagnetic data from the hinterland of the Cantabrian Orocline, which they argue supports such a 90° change in the stress field and therefore a purely secondary cause for the observed arc. Such a model of purely secondary rotations is at odds with a more progressive model in which rotations are acquired during deformation due to an indentor. The work of Del Greco et al. (2016) in the innermost core of the Cantabrian Orocline further supports two discrete phases of shortening and a nearly orthogonal change in the stress field in order to produce the observed interference folds that are documented throughout the hinge-zone of the orocline. Similarly, Pastor-Galán et al. (2015b) proposed a kinematic model for Cantabrian Orocline formation that was facilitated by a regional 90° change in the stress-field at ca. 310 Ma, which led to along strike buckling of the Variscan orogen accommodated by large-scale shear zones (Fig. 14.8g).

Though not specifically advocating a ribbon continent model, Pereira et al. (2014) published new geochronologic and petrologic work from Variscan basement found in the Pyrenees, which they argue supports the existence of oceanic lithosphere involvement in late Variscan magmatism. Like the ribbon continent model of Johnston et al. (2013), their model requires oceanic lithosphere to exist east of the present-day Iberian Massif. Pereira et al. (2015) argued that forces related to roll-back caused by a north-dipping subduction zone near the western corner of the newly developing Paleotethys Ocean would have subsequently driven the formation of the Cantabrian Orocline. This model is a modification of the Gutiérrez-Alonso et al. (2008) Pangea self-subduction model (Fig. 14.8h). In the self-subduction model, Iberia was paleogeographically positioned close to the center of the Pangea supercontinent during orocline formation. The east margin of the supercontinent was characterized by a westward-tapering Tethyan oceanic embayment that pinched out near Iberia. The Tethys was inferred to have had an E-W trending mid-ocean ridge; a north-dipping subduction zone along its northern margin in which Laurussia was the overriding plate; and a passive southern margin developed along the Gondwanan portion of Pangea. This unique paleogeography of the Tethyan realm would have resulted in the subduction of the Tethyan mid-ocean ridge to the north, resulting in Pangean oceanic lithosphere being subducted beneath the Pangean continental crust of Laurasia, a process referred to as ‘self-subduction’. Because of the continuity of the oceanic lithosphere with the Pangean continental lithosphere across the northern Gondwanan passive margin, subduction related slab pull forces would have transmitted into continental Pangea. The result would have been a profound change in the Pangean strain regime, with shortening and contraction within the inner region of Pangea that surrounded the western end of the Tethys, and extension around the supercontinents periphery. Ultimately, contraction within the inner tract of the Pangean superplate would have given rise to the Iberian Orocline(s). Slab pull forces subsequently resulted in failure of the continental lithosphere along what was the northern Gondwanan margin, creating a rift basin south of and parallel to the southern Tethys margin. Self-subduction ended with the formation of the Neotethys mid-ocean ridge, which separated continental Pangea from the subducting slab.

To account for the large-scale rotations associated with orocline development, many authors have advocated for orocline formation models that rely on a combination of shear faulting, oblique convergence and transpression as a means of inducing secondary rotation. Martínez-Catalán (2011) developed a model that involves dextral transpression that he links to an intercontinental transform that formed between Gondwana and Laurussia after final closure of the Rheic Ocean (Fig. 14.8i). A rigid strut trapped within this large shear system would have subsequently initiated regional rotation and arc formation (Martínez-Catalán et al. 2015), similar to some of the previously discussed indentor models. In the model presented by Martínez-García (2013), the shear system is referred to as the North Iberian Megashear and is characterized by a series of near-vertical strike-slip faults that help to accommodate rotation around a vertical-axis—similar to a flexural slip model for fold formation (Fig. 14.8j). In this scenario the belt started out with a roughly linear NW-SE orientation and was subsequently folded due to drag along the megashear. This shear caused CW rotation in the north and CCW rotation in the south. More recently, Arenas et al. (2014) presented data from the Rheic suture of northern Iberia, which they argue records two discrete phases of high pressure activity that they relate to successive collision events between Gondwana and Laurussia. They argue that these collision events were oblique in nature and were separated by a minor phase of extension and the formation of pull-apart basins. Oroclinal bending would have occurred during the second phase of oblique convergence in the latest Carboniferous. Chopin et al. (2014) link oroclinal bending in Iberia to deformation in the Rehamma Massif in Morocco and the Alleghenian thrust system of North America. They argue for the collision of Gondwana with a previously assembled European Variscan belt in the late Carboniferous, while penecontemporaneously dextral deformation is dominating the Alleghenian of North America. This phase was followed by a change in the stress field, likely due to the counterclockwise rotation of Gondwana, which resulted in a more head-on collision between Gondwana and Laurentia and a final phase of dextral shear in the Variscan of Iberia as the plate-scale kinematics changed. Edel et al. (2015) present new paleomagnetic data from the Catalan Coast Ranges that they argue supports a secondary rotation model for the Cantabrian Orocline that they also link to late-stage north-south shortening due to larger continent-scale transpression and dextral shearing within the European plate during final Pangea amalgamation. In a recent review article on the tectonic evolution of the Variscan of Iberia, Diez-Fernández et al. (2016) present a similar model in which the bending of the

Cantabrian Orocline is due to late Variscan strike-slip tectonics that ultimately segmented the Variscan hinterland of Iberia into the complex network of lithotectonic domains seen today.

A pure lithospheric buckling model for oroclinal development was first proposed by Gutiérrez-Alonso et al. (2004) who argued for thick-skinned deformation of the entire lithosphere (Fig. 14.8k). Such a kinematic model involves lithospheric-scale rotation of the orogen limbs, with extension and thinning in the outer arc, and coeval shortening and thickening in the inner arc (Julivert and Marcos 1973; Julivert and Arboleya 1986; Alvarez-Marron and Perez-Estaún 1988; Gutiérrez-Alonso et al. 2015; Pastor-Galán et al. 2012). If buckling occurred at the lithosphere scale, thickening beneath the inner arc would have resulted in gravitational instability causing detachment and removal of the mantle lithosphere (and perhaps even the lower crust), in turn resulting in upwelling of the asthenosphere. This upwelling is recorded in the voluminous Late Carboniferous–Permian magmatism found throughout the Variscan fold-and-thrust belt (Fernández-Suárez et al. 2000, 2011; Gutiérrez-Alonso et al. 2004, 2011a, b). This hypothesis explains many unusual geologic phenomena found in the core of the Cantabrian orocline, including uncommon high coal ranks in the uppermost Carboniferous continental basins (Colmenero and Prado 1993; Colmenero et al. 2008); gold mineralization in the foreland fold and thrust belt (Martín-Izard et al. 2000); remagnetization recorded in Late Carboniferous–Permian strata (Weil and Van der Voo 2002); dolomitization along late breaching and out-of-sequence thrusts (Gasparrini et al. 2006; Lapponi et al. 2014; Blanco-Ferrera 2017); the tectonothermal evolution of the Cantabrian Oroclines core as recorded by cleavage development (Valín et al. 2016) and the thermal history of xenoliths found in Mesozoic diatreme samples (Puelles et al. 2017); post-orogenic topographic elevation (Muñoz-Quijano and Gutiérrez-Alonso 2007); and the late onset of foreland magmatism in the Cantabrian Zone foreland (Gutiérrez-Alonso et al. 2004, 2011a, b; Cuesta and Gallastegui 2007). Delayed onset of magmatism within the foreland is interpreted to reflect initial thickening of the lithospheric mantle in the core of the orocline, forming an orogenic root that subsequently became gravitationally unstable (Fig. 14.8). Subsequent felsic melts are attributed to melting of the fertile (pelite- and greywacke-rich) middle crust upon upward migration of the thermal anomaly above a high-standing asthenosphere.

These mafic rocks and their accompanying granitoids are interpreted as a byproduct of decompressive mantle and lower crustal melting, caused by lithospheric extension around the outer orocline arc during buckling (Fig. 14.8). Thinning of the lithosphere in the outer arc, a concomitant rise of the asthenosphere, and coupled intrusion of gabbro resulted in a regionally elevated geothermal gradient across the arc. This increase in thermal energy resulted in melting of middle-upper crustal rocks still hot from Variscan orogenesis, which led to intrusion of felsic, crustal derived magmas into the outer arc of the orocline between 305 and 295 Ma.

Each of the above models is biased in their consideration of the nature and number of secondary oroclines inferred to have formed during the final stages of Variscan tectonics in Iberia. All of the previously discussed models consider the northern Cantabrian Orocline as a secondary featured that underwent some amount of vertical axis rotation subsequent to main Variscan collisional event; whereas few of the models argue explicitly for a second orocline in central Iberia—the so-called Central Iberian Arc (e.g., Aerden 2004; Martínez-Catalán 2011; Shaw et al. 2012; Johnston et al. 2013). As highlighted by Johnston et al. (2013), if the Central Iberian Arc is truly a secondary feature, any viable tectonic model must start with an Iberian Variscan belt that is greater than 2000 km long, which is paleogeographically absent in nearly all of the existing tectonic models for the Variscan. Consequently, it is vitally important to continue to test whether the Central Iberian Arc is in fact a secondary feature, or alternatively a primary structure of the Iberian Massif (e.g. Pastor-Galán et al. 2015a; in press; Shaw et al. 2016; Dias et al. 2016).

14.5 Existing Constraints on Current and Future Models of Arc/Orocline Formation in Iberia

- The Cantabrian Zone represents a secondary orocline that resulted from bending or buckling of a roughly linear orogenic belt, that had major thrusts and faults oriented north-south in present-day coordinates.
- The vertical axis rotations that led to oroclinal bending/buckling are constrained to a time span of c.a. 15 m.y., and likely no longer than 20 m.y., between 315 and 295 Ma.
- Paleomagnetic, structural and sedimentological patterns/geometries around the Cantabrian Orocline match predictions of a secondary oroclinal model.
- Penecontemporaneous with the formation of the Cantabrian Orocline, was widespread magmatism emplaced throughout Iberia, and which youngs progressively towards the core of the Cantabrian Orocline.
- The Central Iberian arc, if caused by vertical axis rotations, formed prior to the Cantabrian Orocline and likely before 318 Ma, without any other kinematic constraints up to date.

14.5.1 Outstanding Questions

- What is the geometry and geographic extent of the Central Iberia Arc? More specifically, what is the orientation of the axial trace of the arc and where is its hinge zone?
- What is the kinematic nature of the Central Iberian Arc in terms of possible secondary rotations?
- How extensive are the rotations associated with the northern and southern limbs of the Cantabrian Orocline? Does rotation extend out and incorporate all of the major Variscan tectonostratigraphic belts, or is it restricted to only the inner most zones?
- What are the amounts of displacement, timing and kinematics of the major shear zones across the Variscan of Iberia, are their motions coupled, and are they involved in oroclinal bending?
- With respect to present-day coordinates, what was the orientation of maximum shortening during formation of the Cantabrian Orocline? Such information will help determine if orocline formation was due to a bending mechanism with loading perpendicular to the trend of the initial belt, or a buckling mechanism with loading parallel to the trend of the initial belt.
- How do the tectonostratigraphic zones of northern and southern Iberia correlate given the possibility that the Central Iberian arc may be a secondary feature.
- How do we better constrain the paleogeography of Gondwana, Laurussia and the various blocks that make up Variscan Europe in the time from the Devonian, through the Carboniferous, and into the Permian.
- What was the nature of the lithosphere to the east of the Iberian Massif during the Carboniferous and Permian. Was it positioned in an intercontinental setting, or was it bound by oceanic lithosphere that would have accommodated ribbon continental buckling.
- How do we better constrain the nature of the basement below and to the east of the Variscan foreland.
- What tests can be applied to the indentor models that would show whether indentation contributed to bending one or more of the Iberian oroclines.

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