Buckling an orogen: The Cantabrian Orocline

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ABSTRACT

The Paleozoic Variscan orogeny was a large-scale collisional event that involved amalgamation of multiple continents and micro-continents. Available structural, geological, geochemical, and geophysical data from Iberia are consistent with a model of oroclinal bending at the lithospheric scale of an originally near-linear convergent margin during the last stages of Variscan deformation in the late Paleozoic. Closure of the Rheic Ocean resulted in E-W shortening (in present-day coordinates) in the Carboniferous, producing a near linear N-S–trending, east-verging orogenic belt. Subsequent N-S shortening near the Carboniferous-Permian boundary resulted in oroclinal bending, highlighted by the formation of the Cantabrian Orocline. Together, these data constrain oroclinal bending in Iberia to have occurred during the latest Carboniferous over about a 10-million-year time window, which agrees well with recent geodynamical models and structural data that relate oroclinal bending with lithospheric delamination in the Variscan. This late-stage orogenic event remains an enigmatic part of final Pangaea amalgamation.

INTRODUCTION

Orogenic belts that are bent in plan view are a ubiquitous feature of recent and ancient orogens (e.g., Marshak, 2004; van der Voo, 2004; Sussman and Weil, 2004; Weil and Sussman, 2004). Where a bend is formed by buckling of an originally linear orogen about a vertical axis of rotation, it is classified as an orocline (Carey, 1955, 1958). Oroclines are amongst the largest geological structures on Earth and have formed from Archean to recent times. Their existence has profound implications for the tenets of plate tectonics and challenges the fundamental assumption of plate rigidity.

We describe the well-studied Cantabrian Orocline of northern Spain. This is one of the first bent orogens reported in geoscience literature, referred to as the "Asturian Knee" by Eduard Suess in the late nineteenth century in his massive work *Das Antlitz der Erde* (1885–1908) (translated to English in 1909). Suess recognized that the structures, now attributed to the Early Carboniferous collision between Laurussia and Gondwana during Pangea amalgamation, define a significant bend in northern Iberia. Since Suess' description, the curved portion of the Variscan orogen has been the object of numerous studies aimed at unraveling the timing and kinematics of orogenic development, with more recent emphasis on exploring the orogen's impact at the lithospheric scale (e.g., Julivert, 1971; Julivert and Marcos, 1973; Ries et al., 1980; Pérez-Estaún et al., 1988; Weil et al., 2000, 2001; Gutiérrez-Alonso et al., 2004, 2011a, 2011b; Johnston and Gutiérrez-Alonso, 2010). In the following sections, we summarize the results of recent studies in the Cantabrian Orocline that help constrain its timing, kinematics, and geometry. We also utilize insights from analogue experiments to develop models of orocline formation and speculate on possible causes of oroclinal bending. Finally, we consider the assumption of plate rigidity in the light of our current understanding of the Cantabrian Orocline.

THE CANTABRIAN ARC OROCLINE

The Cantabrian Orocline (Fig. 1) defines the core of a larger curved orogenic system that weaves through Western Europe, and it is located at the apex of the Ibero-Armorican Arc (Fig. 1). The orocline is recognized by geometrical changes in the structural trend of thrust-related folds that formed during the Carboniferous Variscan orogeny. The orocline has a convex-to-the-west shape, an E-W axial trace, and an isoclinal geometry in plan view. Both the northern and southern limbs of the orocline strike E-W, thus defining an arc with 180° of curvature. The Cantabrian Orocline is characterized as a foreland fold-thrust belt with thrust vergence toward the oroclinal core (Julivert, 1971). Thrusts imbricate a Carboniferous foreland basin sequence, an underlying Lower Paleozoic passive margin sequence, and a basal Ediacaran slate belt. The distribution of sedimentary facies and paleocurrent data show that the Lower Paleozoic passive margin faced outward, away from the core of the orocline (Shaw et al., 2012). The Variscan metamorphic hinterland surrounds the core of the orocline to the west and south, and is overthrust in the west by ophiolitic assemblages along foreland-verging thrusts. Recent structural (Aerden, 2004; Martínez-Catalán, 2011) and sedimentological (Shaw et al., 2012) studies in central and southern Iberia have revitalized an early suggestion of du Toit's (1937) that the Cantabrian Orocline continues to the south, forming a second bend (the Central Iberian Orocline) that together define a continental-scale S-shaped orocline pair.

KINEMATICS AND TIMING

To constrain the kinematics and timing of orocline development, two approaches have been used that yield complementary results: joint analysis and paleomagnetism in pre- syn- and post-orocline sedimentary sequences (Fig. 2).

Joint sets are developed in strata that span the duration of Variscan orogenesis, including late-stage orocline formation (Pastor-Galán et al., 2011). Joints in structurally imbricated strata

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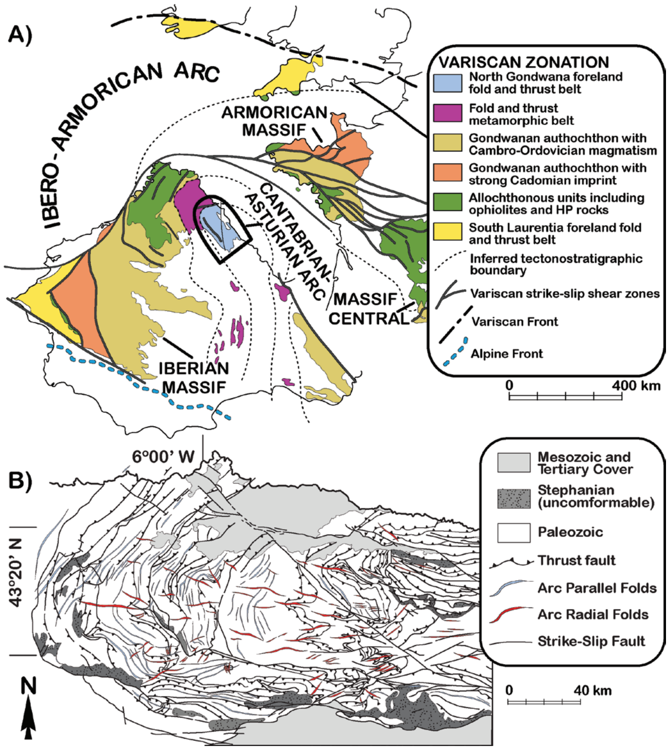

Figure 1. (A) Correlation of tectonostratigraphic zones across the Variscan orogen in southwestern Europe (modified from Franke, 1989; Martínez-Catalán et al., 2007). Iberia has been restored to its paleogeographic position prior to the opening of the Cantabrian Sea (Bay of Biscay). Inset box indicates the location of Cantabrian Orocline. (B) Simplified structural map of the Cantabrian Orocline, highlighting the geometry of major thrusts and the orientation of major folds.

that are continuously exposed around the orocline are shown to be related to thrust formation and buckling. Thrust-related synorogenic strata constrain thrust fault formation to have occurred by 315 to 310 Ma (e.g., Alonso, 1987; Keller et al., 2007; Merino-Tomé et al., 2009). In pre-orocline sedimentary sequences, two orthogonal joint sets are identified, one parallel to and another normal to arc-parallel thrust traces and the axes of thrust-related fault-bend folds. The joint sets systematically trace the curvature of the arc, changing orientation with regional strike around the orocline (Fig. 2). Upper Pennsylvanian strata are deposited in continental basins that unconformably overlie the older, thrust imbricated strata. These strata have younger orthogonal joint sets that trace 60% of total arc curvature (Fig. 2). These sediments are interpreted to have been deposited, and their joint sets developed, during orocline formation (Pastor-Galán et al., 2011). Finally, joint sets in Early Permian strata that unconformably overlie the curved Variscan structures show no systematic change in orientation around the trace of the Cantabrian Orocline and are therefore interpreted to post-date orocline formation (Fig. 2). Hence, the pre-, syn- and post-orocline sedimentary sequences and the joint sets they contain limit the Cantabrian Orocline to have formed after about 315 Ma and prior to the Early Permian (pre-299 Ma). This time frame is consistent with the deposition of Upper Pennsylvanian strata (307 to 299 Ma) during orocline formation.

Paleomagnetic data have also been used to constrain the timing of orocline formation. The rocks of the Variscan foreland in the core of the Cantabrian Orocline were remagnetized during and after early imbricate thrusting, yielding two syntectonic magnetizations that have been used to constrain the kinematics of subsequent deformation (Hirt et al., 1992; Parés et al., 1994; Stewart, 1995; van der Voo et al., 1997; Weil et al., 2000, 2001). In situ paleomagnetic site means were individually restored to a known

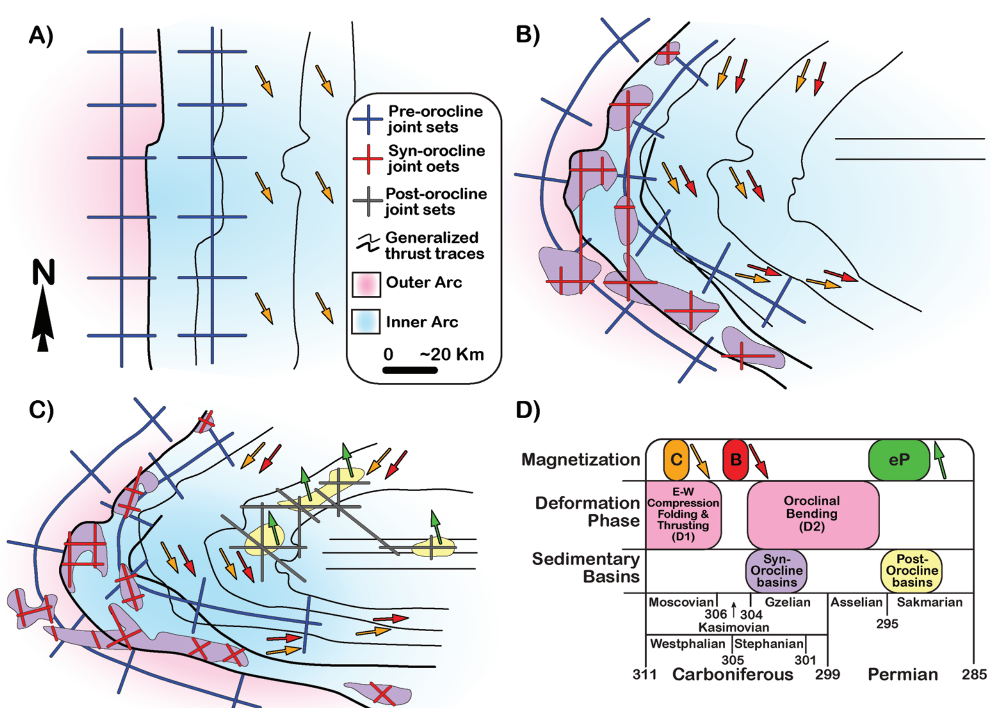

Figure 2. Cartoon summarizing the development of joint sets (Pastor-Galán et al., 2011) and the acquisition of multiple magnetizations (Weil et al., 2001, 2010) in the Cantabrian arc during formation of the Cantabrian Orocline. (A) Joints and paleomagnetic vectors interpreted to develop contemporaneously with formation of a nearly linear Variscan orogen in pre-Moscovian and Moscovian times. (B) Arc during the uppermost Kasimovian and Gzhelian times when between 30% and 50% of the arc's present-day curvature was attained, deposition of the Stephanian B–C basins occurred, and development of fold-axis subparallel and subperpendicular Stephanian joint sets were formed. (C) Present-day geometry of the Cantabrian Orocline and the orientation of the Early Permian paleomagnetic vectors showing no rotation. (D) Proposed timeline for successive magnetizations recorded in the Cantabrian Orocline and their relationships to the main phases of oroclinal formation and formation of sedimentary basins.

reference direction based on observed geologic structures (e.g., local fold axis orientation) and geometric constraints. Such restorations have an intrinsic error based on restoration path uncertainty, constraints on the reference direction, and the timing of magnetization acquisition, all of which have been well established in the Cantabrian Orocline (e.g., van der Voo et al., 1997; Weil et al., 2000, 2001; Weil, 2006; Tohver and Weil, 2008). Analyses of paleomagnetic sites from structural domains distributed around the arc of the orocline indicate clockwise rotations in the northern limb of the Cantabrian Orocline, counter-clockwise rotations in the southern limb, and complex interference folding in the hinge zone (Fig. 2). The unconformably overlying Early Permian continental strata from both limbs of the orocline preserve a primary magnetization that records no vertical axis rotation (Weil et al., 2010) (Fig. 2). These data limit orocline development to have started after acquisition of the syntectonic remagnetization of thrust imbricated strata at 315 to 310 Ma and to have ended prior to deposition of the unconformable Early Permian strata at 299 Ma, consistent with the constraints provided by joint-set orientation data.

LITHOSPHERIC RESPONSE

One of the most challenging questions concerning orocline formation is the evolution of their three-dimensional (3-D) geometry. Do oroclines evolve as thick-skinned, lithospheric-scale structures, or are they thin-skinned features that terminate against crustal detachments? Extensive magmatism accompanied formation of the Cantabrian Orocline, which is interpreted to reflect a thick-skinned, lithospheric-scale response to active buckling (Gutiérrez-Alonso et al., 2004, 2011a, 2011b). Syn-orogenic Variscan granitoid magmatism was active from 345 Ma to 315 Ma and recorded the building and collapse of the Variscan belt (Fernández-Suárez et al., 2000). Subsequent post-orogenic magmatism comprises intrusive and volcanic rocks emplaced from 310 to 285 Ma, which are penecontemporaneous with, and slightly post-date, oroclinal buckling. The post-orogenic magmatic record consists of mantle and crustal derived melts that show systematic changes in their age, spatial distribution, petrology, and geochemistry and include significant foreland magmatism in the core of the Cantabrian Orocline (Gutiérrez-Alonso et al., 2011b).

Magmatism began in the orogenic hinterland region with intrusion of mantle and lower crustal derived mafic melts from 310 to 305 Ma (Fig. 3C). 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. 3). Thinning of the lithosphere in the outer arc, a concomitant rise of the asthenosphere, and coupled intrusion of gabbros 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 and led to intrusion of felsic, crustal derived magmas into the outer arc of the orocline between 305 and 295 Ma (Fernández-Suárez et al., 2000; Gutiérrez-Alonso et al., 2011b).

A different (albeit intimately related) magmatic history characterizes the inner arc of the orocline, where magmatism did not begin until 300 Ma and did not end until 285 Ma (Fig. 3D). Magmatism in the core of the orocline (foreland) began with the intrusion of mantle and lower crust-derived mafic rocks and granitoids and with widespread volcanism that continued until 292 Ma (Fig. 3D). This was followed by felsic, crustal-derived leucogranite magmatism that continued for another 7 m.y. in the foreland (Gutiérrez-Alonso et al., 2011b). The 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. 3). Delamination and sinking of the unstable root facilitated upwelling of hot asthenospheric mantle beneath

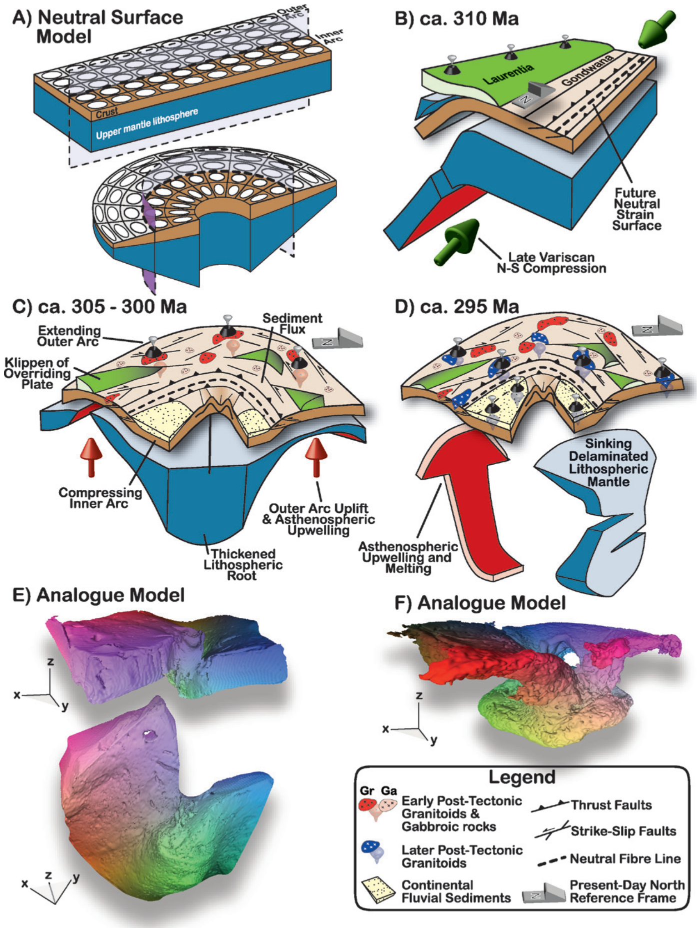

Figure 3. (A) Block diagram depicting the effect of lithospheric bending around a vertical axis and the resultant strain field (modified tangential longitudinal strain). Strain ellipses depict arc-parallel shortening in the inner arc and arc-parallel stretching in the outer arc. Note the different behavior of the mantle lithosphere in the inner and outer arcs and the increase in thickness of mantle lithosphere below the inner arc and thinning below the outer arc. (B) Snapshot illustration of arc development starting with a linear belt resulting from a Gondwana–Laurentia collision. (C) Second snapshot illustrating oroclinal bending, which causes lithospheric stretching in the outer arc and thickening beneath the inner arc (Gutiérrez-Alonso et al., 2004). (D) The final stage of oroclinal bending, depicting delamination and collapse of thickened lithospheric root beneath the inner arc, replacement of sinking lithosphere by upwelling asthenospheric mantle, and associated magmatism in the inner and outer arc regions. (E) Two tomographic views of the analogue modeled mantle lithosphere geometry after buckling around a vertical axis where the lithospheric root is developed under the inner arc (top—frontal view from the concave part of the model; bottom—view from below); 3-D coordinate axes given. (F) Tomographic 3-D image of the delaminated lithospheric root obtained with analogue modeling; 3-D coordinate axes given.

the foreland core of the orocline, giving rise to mantle-derived mafic magmatism and melting of the lower crust. The subsequent felsic melts are attributed to melting of the fertile (pelite- and greywacke-rich) middle crust upon upward migration of the thermal anomaly above the high-standing asthenosphere.

The study of Sm/Nd isotopes from mantle-derived rocks provides further evidence of mantle lithosphere involvement during orocline development (Gutiérrez-Alonso et al., 2011a; Ducea, 2011). Pre-Variscan mantle-derived volcanic rocks indicate that the mantle lithosphere in NW Iberia was emplaced, or metasomatized, at ca. 1.0 Ga, while post-Variscan mantle-derived magmatic rocks yield neodymium model ages (TDM) of ca. 0.3 Ga. This change in mantle lithosphere age indicates that orocline formation was coeval with removal of an older mantle lithosphere and its subsequent replacement by a new, juvenile mantle lithosphere (Fig. 3D). The syn-orocline mantle-derived melts were contaminated by crustal sources during orocline formation and yield model ages that span the inferred age of the underlying pre-Variscan lithosphere and the new lithospheric mantle. The resultant contamination indicates that melting of the continental mantle lithosphere and lower crust, and the subsequent mixing with upwelling asthenosphere, is likely responsible for generating the new lithospheric mantle (Gutiérrez-Alonso et al., 2011a).

Major topographic changes in Earth's surface usually reflect lithospheric processes (Jiménez-Munt and Platt, 2006); therefore, the major changes in lithosphere thickness and shape associated with oroclinal buckling likely produced important topographic changes that would be recorded in syn-orocline deposits. As stated previously, oroclinal bending resulted in lithospheric thinning in the outer arc and thickening in the inner arc. Due to the more buoyant nature of the thinner outer arc (underlain by hot asthenosphere) compared to the thicker inner arc (underlain by a growing lithospheric root), a regional topographic slope was established from a high in the outer arc to a low in the inner arc (Fig. 3C). This orocline-induced topographic gradient is recorded in the thick, conglomerate-rich continental deposits of Upper Pennsylvanian age preserved throughout the inner arc. Subsequent floundering of the lithospheric root under the inner arc (Fig. 3D), and its replacement by hotter, more buoyant, asthenospheric mantle, resulted in a topographic inversion that is recorded in the unconformable Lower Permian sediments present in this region that postdate the orocline formation (Weil et al., 2010). These topographic changes agree with simple numerical isostatic balance models of the lithosphere thickness variations inferred from geological data (Muñoz-Quijano and Gutiérrez-Alonso, 2007).

The structural, paleomagnetic, geochronologic, and geochemical data summarized in this section indicate that mantle replacement and orocline formation were coeval, suggesting that the two processes were linked. Hence, magmatic, isotopic, and sedimentological data are all consistent with our model of Cantabrian Orocline formation involving the entire lithosphere.

ANALOGUE MODELING

One of the lingering questions regarding lithospheric-scale orocline development is the physical and geometric response to lithospheric buckling. To better understand the lithospheric consequences of forming this scale of bending, we used thermo-mechanical analogue modeling to gain insight into the feasibility of lithospheric-scale orocline formation. Plasticines with contrasting rheological behavior scaled to the mechanical properties of the crust, mantle lithosphere, and sub-lithospheric mantle were employed to model lithospheric-scale buckling about a vertical axis (Figs. 3E and 3F). The modeling set-up imparted a vertical thermal gradient during experimental runs. After buckling, the models were imaged using 3-D computer tomography (CT). Details of the experiments can be found in Pastor-Galán et al. (2012).

The experimental set-up consisted of a 30 × 12 × 8 cm elongate model plate (crust and lithospheric mantle and its underlying asthenospheric mantle), which was shortened into a buckle fold about a vertical axis. Multiple experimental set-ups were used with variable strain rates and lithospheric thicknesses. All experimental runs were performed under a constant temperature profile designed to maintain a stable viscosity contrast between the different layers. Model results indicate that, regardless of layer thicknesses used, or the strain rate employed during oroclinal buckling, the mantle lithosphere thickened beneath the orocline core and thinned around the outer orocline arc (Fig. 3). Thinning in the outer arc was accommodated by radial tension fractures, whereas thickening in the inner arc was dependent upon initial lithosphere thickness; initially thick lithospheric mantle thickened through formation of a tight, steeply plunging conical fold, while initially thin lithospheric mantle thickened through formation of recumbent conical nappes. Importantly, the lithospheric-scale processes inferred to have taken place during generation of the Cantabrian Orocline are well reproduced in the analogue experiments.

WHAT CAUSED THE CANTABRIAN ARC OROCLINE?

All available structural, geological, geochemical, and geophysical data are consistent with the Cantabrian Orocline developing by buckling of an originally linear orogen (Weil et al., 2000, 2001; Gutiérrez-Alonso et al., 2004, 2008, 2011a, 2011b; Martínez-Catalán, 2011). The question remains, however: What was the geodynamic setting that gave rise to the buckle? Iberia lay 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 is inferred to have had an E-W trending mid-ocean ridge (Gutiérrez-Alonso et al., 2008), a north-dipping subduction zone along its northern margin that descended beneath the Laurasian portion of Pangea, and a passive southern margin developed along the Gondwanan portion of Pangea.

The unique paleogeography of the Tethyan realm is the basis for one possible explanation for orocline formation. Subduction of the Tethyan mid-ocean ridge to the north resulted in Pangean oceanic lithosphere being subducted beneath the Pangean continental crust of Laurasia, a process referred to as self-subduction (Gutiérrez-Alonso et al., 2008) (Fig. 4). Because of the continuity of the oceanic lithosphere with Pangean continental lithosphere across the northern Gondwanan passive margin, subduction-related slab pull forces are predicted to 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

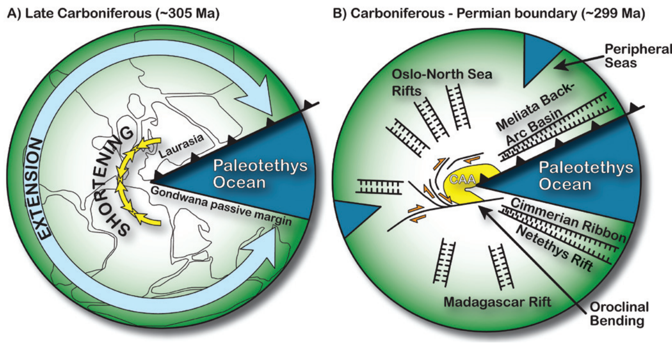

Figure 4. Schematic diagrams showing simplified Pangaea reconstructions for (A) the middle Pennsylvanian at 305 Ma, and (B) the Carboniferous-Permian boundary at 299 Ma (Gutiérrez-Alonso et al., 2008). Cartoon depiction of Pangea configuration given in (A) for geographic reference. CAA—Cantabrian-Asturian arc.

supercontinent's periphery (Fig. 4A). We suggest that it is the contraction within the inner tract of the Pangean superplate that gave rise to the Cantabrian Orocline, its concomitant lithospheric delamination, and its related magmatic activity. Late Palaeozoic radial rift basins characterize the periphery of northern Pangea, which supports the idea of widespread extension around the edges of the superplate (Fig. 4B). 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. This final stage is likely recorded in the widespread Permian-Carboniferous unconformity in the continental basins of Europe.

OROCLINES: THICK OR THIN SKINNED?

Curved mountain belts that are demonstrably the result of the buckling of originally linear orogens have commonly been interpreted as thin-skinned features involving only the uppermost crust. Thin-skinned interpretations of oroclines are reconciled with the plate tectonic assumption of plate rigidity by having the orocline form above a crustal detachment that separates the deforming orogen from the underlying plate. However, this model commonly results in important space problems associated with large-scale thrust sheet rotation. It is demonstrated that formation of the Cantabrian Orocline was concomitant with profound magmatism, and deformation best explained as the result of buckling of the entire lithosphere about a vertical axis. Lithospheric buckling can also explain other ancient oroclines, such as the Alaskan oroclines of the North American Cordillera (Johnston, 2001, 2008) and the New England Orocline (Cawood et al., 2011), and provides a model for explaining magmatism and deformation attending currently forming oroclines, like the East Carpathian (Fillerup et al., 2010), the Calabria (Johnston and Mazzoli, 2009), and the Melanesian oroclines (Johnston, 2004).

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REFERENCES CITED

Aerden, D.G.A.M., 2004, Correlating deformation in Variscan NW-Iberia using porphyroblasts; implications for the Ibero-Armorican arc: Journal of Structural Geology, v. 26, p. 177–196.

Alonso, J.L., 1987, Sequences of thrust and displacement transfer in the superposed duplexes of the Esla Nappe Region (Cantabrian Zone, NW Spain): Journal of Structural Geology, v. 9, p. 969–983.

Carey, S.W., 1955, The orocline concept in geotectonics: Proceedings of the Royal Society of Tasmania, v. 89, p. 255–288.

Carey, S.W., 1958, A tectonic approach to continental drift, *in* Carey, S.W., ed., Continental Drift: A symposium: Tasmania, Hobart, p. 177–355.

Cawood, P.A., Pisarewsky, S.A., and Leitch, E.C., 2011, Unraveling the New England orocline, east Gondwana accretionary margin: Tectonics, v. 30, TC5002, 15 p., doi: 10.1029/2011TC002864.

Ducea, M.N., 2011, Fingerprinting orogenic delamination: Geology, v. 39, p. 191–192, doi: 10.1130/focus022011.1.

du Toit, A.L., 1937, Our Wandering Continents: Edinburgh, Oliver and Boyd, 366 p.

Fernández-Suárez, J., Dunning, G.R., Jenner, G.A., and Gutiérrez-Alonso, G., 2000, Variscan collisional magmatism and deformation in NW Iberia: Constraints from U-Pb geochronology of granitoids: Journal of the Geological Society, v. 157, p. 565–576, doi: 10.1144/jgs.157.3.565.

Fillerup, M.A., Knapp, J.H., Knapp, C.C., and Raileanu, V., 2010, Mantle earthquakes in the absence of subduction? Continental delamination in the Romanian Carpathians: Lithosphere, v. 2, p. 333–340, doi: 10.1130/L102.1.

Franke, W., 1989, Variscan plate tectonics in Central Europe—current ideas and open questions: Tectonophysics, v. 169, p. 221–228.

Gutiérrez-Alonso, G., Fernández-Suárez, J., and Weil, A.B., 2004, Orocline triggered lithospheric delamination, *in* Sussman, A.J., and Weil, A.B., eds., Orogenic curvature: Integrating paleomagnetic and structural analyses: Geological Society of America Special Paper 383, p. 121–131, doi: 10.1130/0-8137-2383-3(2004) 383[121:OTLD] 2.0.CO;2.

Gutiérrez-Alonso, G., Fernández-Suárez, J., Weil, A.B, Murphy, J.B, Nance, R.D., Corfu, F., and Johnston, S.T., 2008, Self-subduction of the Pangaean global plate: Nature Geoscience, v. 1, p. 549–553, doi: 10.1038/ngeo250.

Gutiérrez-Alonso, G., Murphy, B., Fernández-Suárez, J., Weil, A.B., Franco, M.P., and Gonzalo, J.C., 2011a, Lithospheric delamination in the core of Pangea: Sm-Nd insights from the Iberian mantle: Geology, v. 39, p. 155–158, doi: 10.1130/G31468.1.

Gutiérrez-Alonso, G., Fernández-Suárez, J., Jeffries, T.E., Johnston, S.T., Pastor-Galán, D., Murphy, J.B., Franco, M.P., and Gonzalo, J.C., 2011b, Diachronous post-orogenic magmatism within a developing orocline in Iberia, European Variscides: Tectonics v. 30, TC5008, 17 p., doi: 10.1029/2010TC002845.

Hirt, A.M., Lowrie, W., Julivert, M., and Arboleya, M.L., 1992, Paleomagnetic results in support of a model for the origin of the Asturian Arc: Tectonophysics, v. 213, p. 321–339.

Jiménez-Munt, I., and Platt, J.P., 2006, Influence of mantle dynamics on the topographic evolution of the Tibetan Plateau: Results from numerical modeling: Tectonics, v. 25, TC001963, doi: 10.1029/2006.

Johnston, S.T., 2001, The great Alaskan terrane wreck: Reconciliation of paleomagnetic and geological data in the northern Cordillera: Earth and Planetary Science Letters, v. 193, p. 259–272, doi: 10.1016/j.bbr.2011.03.031.

Johnston, S.T., 2004, The d'Entrecasteaux orocline and rotation of the Vanuatu–New Hebrides arc: An oroclinal orgy and analogue for Archean craton formation, *in* Sussman, A.J., and Weil, A.B., eds., Orogenic curvature: Integrating paleomagnetic and structural analyses: Geological Society of America Special Paper 383, p. 225–236.

Johnston, S.T., 2008, The Cordilleran ribbon continent: Annual Reviews in Earth & Planetary Sciences, v. 36, p. 495–530, doi: 10.1146/annurev.earth.36.031207.124331.

Johnston, S.T., and Gutiérrez-Alonso, G., 2010, The North American and Variscan orogens: Contrasting interpretations of similar mountain systems: Gondwana Research, v. 17, p. 516–525.

Johnston, S.T., and Mazzoli, S., 2009, The Calabrian Orocline: Buckling of a previously more linear orogen, *in* Murphy, J.B., Keppie, J.D., and Hynes, A.J., eds., Ancient Orogens and Modern Analogues: London, Geological Society Special Publication 327, p. 113–125, doi: 10.1144/SP327.7.

Julivert, M., 1971, Décollement tectonics in the Hercynian Cordillera of NW Spain: American Journal of Science, v. 270, p. 1–29.

Julivert, M., and Marcos, A., 1973, Superimposed folding under flexural conditions in the Cantabrian Zone (Hercynian Cordillera, northwest Spain): American Journal of Science, v. 271, p. 353–375.

Keller, M., Bahlburg, H., Reuther, C.D., and Weh, A., 2007, Flexural to broken foreland basin evolution as a result of Variscan collisional events in northwestern Spain, *in* Hatcher, R.D., Carlson, M.P., McBride, J.H., and Martínez Catalán, J.R., eds., 4-D Framework of Continental Crust: Geological Society of America Memoir 200, p. 489–510.

Marshak, S., 2004, Arcs, oroclines, salients, and syntaxes—The origin of map-view curvature in fold-thrust belts, *in* McClay, K.R., ed., Thrust Tectonics and Petroleum Systems: American Association of Petroleum Geologists Memoir 82, p. 131–156.

Martínez Catalán, J.R., 2011, Are the oroclines of the Variscan belt related to late Variscan strike-slip tectonics?: Terra Nova, v. 23, p. 241–247, doi: 10.1111/j.1365-3121.2011.01005.x.

Martínez Catalán, J.R., Arenas, R., Díaz García, F., González Cuadra, P., Gómez-Barreiro, J., Abati, J., Castiñeras, P., Fernández-Suárez, J., Sánchez Martínez, S., Andonaegui, P., González Clavijo, E., Díez Montes, A., Rubio Pascual, F.J., and Valle Aguado, B., 2007, Space and time in the tectonic evolution of the northwestern Iberian Massif: Implications for the Variscan belt, *in* Hatcher, R.D. Jr., Carlson, M.P., McBride, J.H., and Martínez Catalán, J.R., eds., 4-D Framework of Continental Crust: Geological Society of America Memoir 200, p. 403–423, doi: 10.1130/2007.1200(21).

Merino-Tomé, O., Bahamonde, J.R., Colmenero, J.R., Heredia, N., Villa, E., and Farias, P., 2009, Emplacement of the Cuera and Picos de Europa imbricate system at the core of the Iberian-Armorican arc (Cantabrian zone, north Spain): New precisions concerning the timing of arc closure: GSA Bulletin, v. 121, p. 729–751, doi: 10.1130/B26366.1.

Muñoz-Quijano, I.N., and Gutiérrez-Alonso, G., 2007, Modelo de evolución topográfica en el NO de la Península Ibérica durante la delaminación litosférica al final de la Orogenia Varisca: Geogaceta, v. 43, p. 43–46.

Pares, J.M., van der Voo, R., Stamatakos, J., and Perez Estaun, A., 1994, Remagnetizations and postfolding oroclinal rotations in the Cantabrian Asturian arc, northern Spain: Tectonics, v. 13, p. 1461–1471.

Pastor-Galán, D., Gutierréz-Alonso, G., and Weil, A.B., 2011, Orocline timing through joint analysis: Insights from the Ibero-Armorican Arc: Tectonophysics, v. 507, p. 31–46, doi: 10.1016/j.tecto.2011.05.005.

Pastor-Galán, D., Gutiérrez-Alonso, G., Zulauf, G., and Zanella, F., 2012, Analogue modeling of lithospheric scale orocline buckling: Constraints on the evolution of the Ibero Armorican Arc: GSA Bulletin, doi: 10.1130/B30640.1.

Pérez-Estaún, A., Bastida, F., Alonso, J.L., Marquinez, J., Aller, J., Álvarez -Marron, J. Marcos, A., and Pulgar, J.A., 1988, A thin-skinned tectonics model for an arcuate fold and thrust belt: The Cantabrian Zone (Variscan Armorican Arc): Tectonics, v. 7, p. 517–537.

Ries, A.C., Richardson, A., and Shackleton, R.M., 1980, Rotation of the Iberian arc: Paleomagnetic results from north Spain: Earth and Planetary Science Letters, v. 50, p. 301–310.

Shaw, J., Johnston, S.T., Gutiérrez-Alonso, G., and Weil, A.B., 2012, Oroclines of the Variscan orogen of Iberia: Paleocurrent analysis and paleogeographic implications: Earth and Planetary Science Letters, v. 329–330, p. 60–70, doi: 10.1016/j.epsl.2012.02.014.

Stewart, S.A., 1995, Paleomagnetic analysis of fold kinematics and implications for geological models of the Cantabrian/Asturian arc, north Spain: Journal of Geophysical Research, Solid Earth, v. 100, p. 20,079–20,094.

Suess, E., 1909, The Face of the Earth, translated from German (Suess, E., 1885. Das antlitz der erde. F. Tempsky, Vienna) by H.B.C. Sollas and W.J. Sollas: Oxford, Clarendon, 672 p.

Sussman, A.J., and Weil, A.B., 2004, Orogenic curvature: Integrating paleomagnetic and structural analyses: Geological Society of America Special Paper 383, 271 p.

Tohver, E., and Weil, A.B., 2008, A new technique for dating the absolute timing of carbonate remagnetization: Ar-Ar dating of clay transformation in Paleozoic carbonates: Earth and Planetary Science Letters, v. 274, p. 524–530.

van der Voo, R., 2004, Paleomagnetism, oroclines, and growth of the continental crust: GSA Today, v. 14, no. 12, p. 4–9, doi: 10.1130/1052-5173(2004)014<4:POAGOT>2.0.CO;2.

van der Voo, R., Stamatakos, J.A., and Pares, J.M., 1997, Kinematic constraints on thrust-belt curvature from syndeformational magnetizations in the Lagos del Valle Syncline in the Cantabrian Arc, Spain: Journal of Geophysical Research, Solid Earth, v. 102, B5, p. 10,105–10,119.

Weil, A.B., 2006, Kinematics of orocline tightening in the core of an arc: Paleomagnetic analysis of the Ponga Unit, Cantabria Arc, northern Spain: Tectonics, v. 25, TC3012, 23 p., doi: 10.1029/2005TC001861.

Weil, A.B., and Sussman, A.J., 2004, Classifying curved orogens based on timing relationships between structural development and vertical-axis rotations, *in* Sussman, A.J., and Weil, A.B., eds., Orogenic curvature: Integrating paleomagnetic and structural analyses: Geological Society of America Special Paper 383, p. 1–15, doi: 10.1130/0-8137-2383-3(2004)383[1:CCOBOT]2.0.CO;2.

Weil, A.B., van der Voo, R., van der Pluijm, B.A., and Parés, J.M., 2000, The formation of an orocline by multiphase deformation: A paleomagnetic investigation of the Cantabria-Asturias Arc (northern Spain): Journal of Structural Geology, v. 22, p. 735–756.

Weil, A.B., van der Voo, R., and van der Pluijm, B.A., 2001, Oroclinal bending and evidence against the Pangea megashear: The Cantabria-Asturias arc (northern Spain): Geology, v. 29, p. 991–994, doi: 10.1130/0091-7613(2001)029<0991:OBAEAT>2.0.CO;2.

Weil, A.B., Gutiérrez-Alonso, G., and Conan, J., 2010, New time constraints on lithospheric-scale oroclinal bending of the Ibero-Armorican arc: A palaeomagnetic study of earliest Permian rocks from Iberia: Journal of the Geologic Society of London, v. 167, p. 127–143.

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