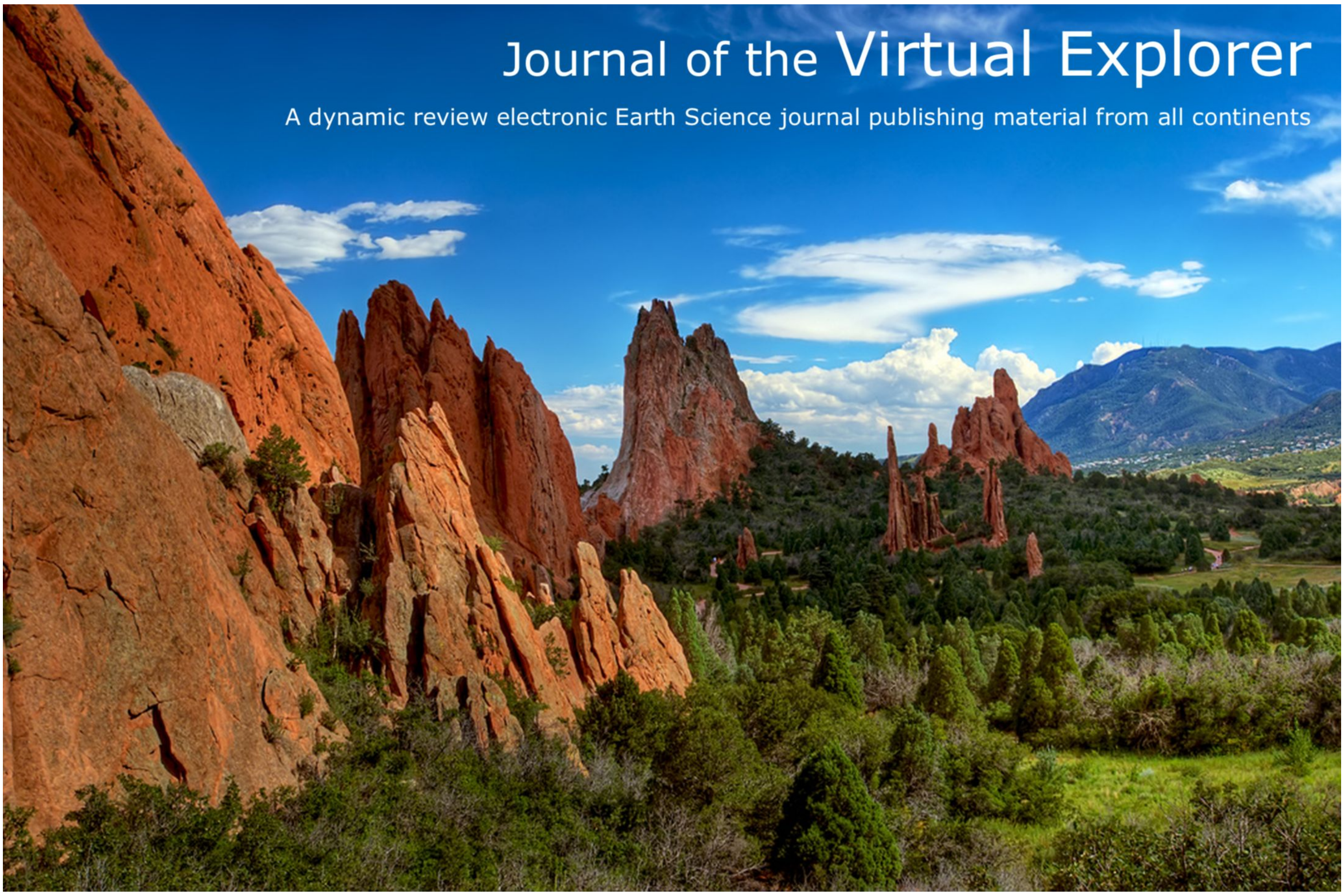


A virtual tour of the Ibero-Armorican orocline

Daniel Pastor-Galán, G. Gutiérrez-Alonso, A.B. Weil, J. Fernández-Suárez, S.T. Johnston, J.B. Murphy

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **43**, paper 2
In: (Eds.) Stephen Johnston and Gideon Rosenbaum, Oroclines, 2012.

Journal of the Virtual Explorer, 2012
Volume 43
Paper 2
http://virtualexplorer.com.au/

A virtual tour of the Ibero-Armorican orocline

Daniel Pastor-Galán
Departamento de Geología, Universidad de Salamanca, Plaza de los Caídos s/n, 37008 Salamanca, Spain.
Email: dpastorgalan@usal.es

G. Gutiérrez-Alonso
Departamento de Geología, Universidad de Salamanca, Plaza de los Caídos s/n, 37008 Salamanca, Spain.

A.B. Weil
Department of Geology, Bryn Mawr College, Bryn Mawr, PA 19010, U.S.A.

J. Fernández-Suárez
Departamento de Petrología y Geoquímica, Universidad Complutense and IGEO-CSIC, 28040 Madrid, Spain.

S.T. Johnston
School of Earth & Ocean Sciences, University of Victoria, PO Box 3065 STN CSC, Victoria BC Canada V8P 4B2

J.B. Murphy
Department of Earth Sciences, St. Francis Xavier University, Chapel Square, Antigonish, Nova Scotia, Canada, B2G 2W5

Abstract: Dynamic content features, such as animations, videos or 3D representations are useful tools to explain dynamic geological processes. Modern technologies permit development of animations that are more illustrative and instructive than the classic static figures traditionally used in scientific papers. In addition, the use of supplemental files in traditional journals, and especially within new electronic journals, permit inclusion of interactive content as an analogue to the dynamic nature of geological processes. We present a collection of dynamic animations based on previous data. These animations are used to deliver ideas about the kinematic and mechanical development of the Ibero-Armorican orocline and to illustrate the complex evolution and timing of orocline formation, its tectonic setting on a regional and global-scale, and its implications for the modification of the lithosphere during orogeny.

Citation: 2012. A virtual tour of the Ibero-Armorican orocline. In: (Eds.) Stephen Johnston and Gideon Rosenbaum, *Journal of the Virtual Explorer*, volume **43**, paper 2, doi: 10.3809/jvirtex.2011.00292

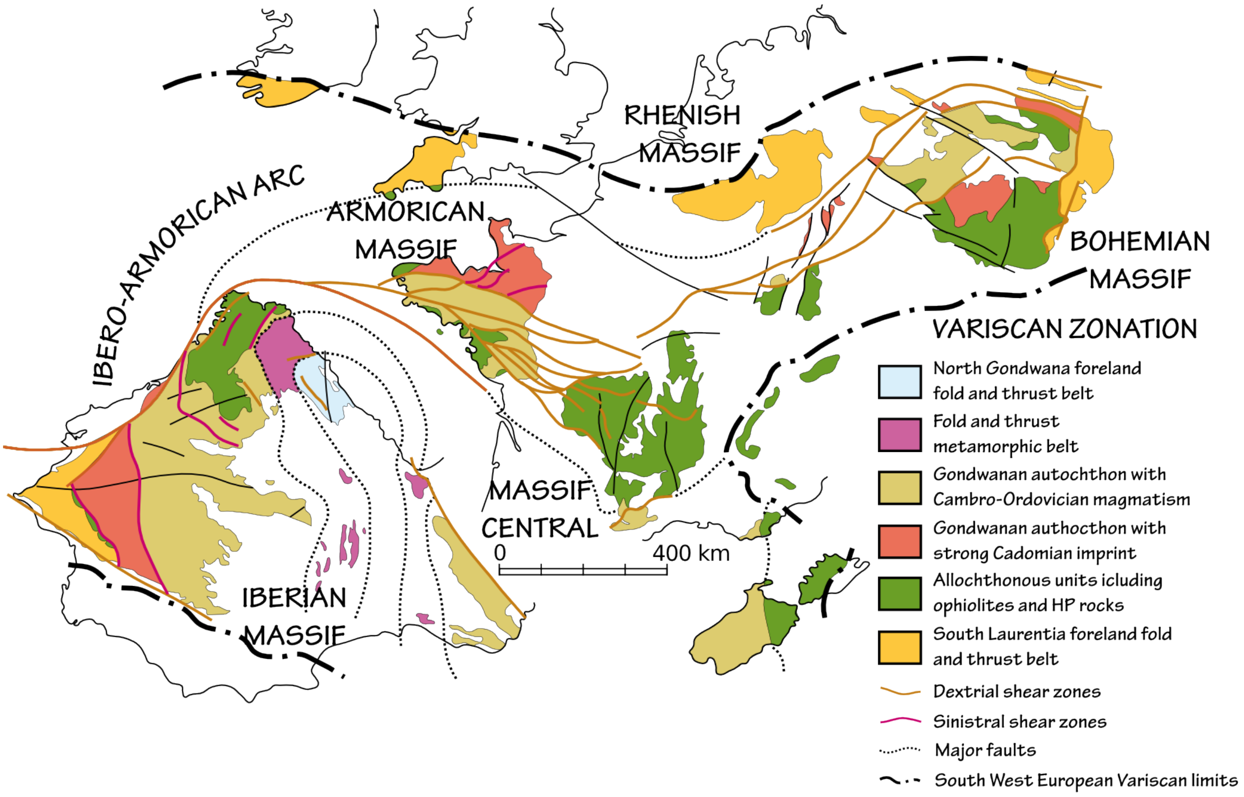
Introduction

The geological sciences have been connected with the visual arts from their infancy as a discipline. Geological studies use visual information to complement text in order to convey complex ideas about solid Earth processes. Until the mid-20th century, illustrations in scientific papers in the natural sciences consisted of sketches, line drawings, or other art forms, such as watercolours or oil paintings (Merriam, 2009). Critical observations such as field relationships, which underpin many important geological interpretations, were presented in this fashion and thus had an inherent subjectivity, or bias. Although a geologist's field notebook is still a collection of sketches and drawings, in modern papers art work has been replaced by digital photographs and computer generated figures. Nonetheless, even in modern papers, the vast majority of figures consist of static representations (sequences of discrete events) that do not accurately portray dynamic geological processes in time and space. However, owing to the rapid development of computer animation technologies, it is now possible to construct dynamic illustrations in the form of animations, videos or 3D representations that provide robust renditions of the dynamic processes that have shaped the Earth’s evolution.

In this paper, we use animations to illustrate the development of curved orogenic belts (in plan view) (e.g. Marshak, 2004; van der Voo, 2004; Sussman and Weil, 2004; Weil and Sussman, 2004). The evolution of curved orogens, which are a ubiquitous feature of recent and ancient mountain belts, has been debated since the 19th century (Suess, 1885; Wegener, 1929; Wilson 1949; Carey, 1955, 1958; Eldredge *et al.*, 1985). Following the kinematic classification of Weil and Sussman (2004), which relies on Carey’s original definition (1955), arcuate orogenic belts that formed by buckling of an originally linear orogen about a vertical axis of rotation are classified as oroclines. Oroclines are amongst the largest geological structures on Earth and have formed from Archean to recent times.

The Ibero-Armorican orocline (Fig. 1) is a curved orogenic system characterized by a 180° bend of the Variscan structural grain (Weil *et al.*, 2001). It was referred to as the "Asturian Knee" by Eduard Suess in the late 19th century in “Das Antlitz der Erde (1885-1908)” (translated into English in 1909). Suess recognized the bend in northern Iberia of structures that are now attributed to the Carboniferous collision between Laurussia and Gondwana during Pangea amalgamation. Since Suess' initial observations, the Ibero-Armorican orocline has been the object of many studies (Brun and Burg, 1982; Dias and Ribeiro, 1995), especially at its core (e.g. Julivert, 1971; Julivert and Arboleya, 1984, 1985; Pérez-Estaún *et al.*, 1988; Weil *et al.*, 2000, 2002; Weil, 2006). The aforementioned studies have attempted to decipher the curved mountain belt kinematics, and a wealth of different hypotheses, spanning the entire classification of Weil and Sussman (2004), have been proposed: (1) a primary arc inherited from a Neoproterozoic embayment (Lefort, 1979); (2) a progressive arc resulting from indentation of a point-shaped block situated either in Gondwana (e.g. Matte and Ribeiro, 1975; Brun and Burg, 1982; Dias and Ribeiro, 1995) or in Avalonia (Simancas *et al.*, 2009), (3) an oblique collision producing a non-cylindrical orogen (Martínez-Catalán, 1990), (4) a thin-skinned origin produced by a progressive change in the transport direction of the thrust units similar to a photographic iris, (Pérez-Estaún *et al.*, 1988), and more recently (5) an orocline formed by the rotation around a vertical axis of an originally linear orogen (Weil, 2006; Weil *et al.*, 2000; 2010; Gutiérrez-Alonso, 2004, 2008, Martínez-Catalán, 2011; Gutiérrez-Alonso *et al.*, 2012). The latter is the only proposed mechanism that conforms to the definition of a true orocline (Weil and Sussman, 2004).

Figure 1. Ibero-Armorican orocline



Tectonostratigraphic location of the Ibero-Armorican orocline (after Weil *et al.* 2010, and Pastor-Galán, 2011) showing the orocline trace and the main structures related to its formation.

The Ibero-Armorican orocline is a central component of the Western European Variscan Belt, a complex continental-scale orogen (1000 km wide and 8000 km long; Fig. 1) that formed through a series of protracted collisional events extending from 420 to 300 Ma (e.g., Franke, 2006, Martínez Catalán *et al.*, 2007 and references therein). Variscan deformation represents the closing of at least two, and possibly four, oceans between Laurentia, Baltica, Gondwana, and several micro-continents during the late Paleozoic amalgamation of the Pangea supercontinent (e.g., Van Staal *et al.*, 1998; Martínez-Catalán *et al.*, 1997, 2007; Matte, 2001). The Ibero-Armorican orocline is characterized by arcuate structural trends that trace an arc from Brittany across the Cantabrian Sea into western Iberia, where it is truncated by the Cenozoic Betics Alpine front in southern Spain. New interpretations, based on the ideas of du Toit (1937), consider the Ibero-Armorican orocline as part of a coupled bend together with the southern Central-Iberian arc (Martínez-Catalán, 2011; Shaw *et al.*, 2012)

Ries and Shackleton (1976) divided the Ibero-Armorican orocline into three structural zones based on a tangential-longitudinal strain model: the outer arc that underwent extension, the inner arc that underwent compression, and a narrow (*ca.* 10 km wide) neutral zone characterized by low strain. In their model, stretching parallel to the outer arc increases away from the core (Ries and Shackleton, 1976), whereas shortening in the inner arc increases towards the core (Julivert and Marcos, 1973; Pastor-Galán *et al.*, 2012a). Outer arc extension was accommodated by dextral strike-slip faulting in the upper crust, and ductile elongation in the lower crust (Gutiérrez-Alonso *et al.*, 2004). At the core of the Ibero-Armorican orocline is the Cantabrian Arc (Weil *et al.*, 2001), which consists of crust considered to have originated along southern (Gondwanan) margin of the Rheic Ocean during the Paleozoic (e.g., Martínez-Catalán, 2002; Robardet, 2003; Murphy *et al.*, 2006).

In this paper we use compilations of data from recent studies that constrain the timing, kinematics, lithospheric geometry and the possible causes of oroclinal bending in the Ibero-Armorican orocline. These constraints are used to develop a virtual tour of the orocline.

Geological Setting

Although heterogeneously deformed by the Late Paleozoic Variscan Orogeny, northwestern Iberia exposes one of the most complete sections of the Paleozoic northern Gondwana passive margin. In this region, Paleozoic rocks lie within the tightly curved Cantabrian Arc. If the arc is restored to a pre-Variscan geometry (Weil *et al.*, 2001; Weil *et al.*, 2010; Gutiérrez-Alonso *et al.*, 2012), the Iberian portion of the Gondwana continental platform is shown to be extensive and positions northwest Iberia adjacent to West Africa along the southern flank of the Rheic Ocean throughout the Paleozoic (Robardet, 2002; Robardet, 2003; Martínez Catalán *et al.*, 2007; Nance *et al.*, 2010).

The Paleozoic rocks of the Iberian Massif are traditionally divided into zones based on differences in their Lower Paleozoic sedimentary successions, which are interpreted to reflect their relative proximity to the Gondwanan margin. From the ancient coastline seaward towards the Gondwanan outer platform, five zones are identified. The Cantabrian Zone (CZ) constitutes the foreland fold and thrust belt. The CZ consists of a sedimentary sequence of pre-orogenic, lower Paleozoic platform sedimentary rocks that thin towards the core of the arc. These pre-orogenic strata are covered by a Carboniferous syn-orogenic sequence and a post-orogenic (Stephanian) continental succession (Pastor-Galán *et al.*, 2011). Structurally, the CZ is characterized by thin-skinned tectonics with a transport direction towards the core of the arc (Pérez-Estaún *et al.*, 1988). The basal thrust for the whole imbricate system is imaged as a flat surface in a deep seismic survey parallel to the axial trace of the Cantabrian Arc (Pérez-Estún *et al.*, 1994). Given the lack of internal strain and metamorphism, and the presence of a complete syn-orogenic sedimentary sequence in the CZ, it is an ideal zone for combined paleomagnetic and progressive deformation structural studies. The West Asturian Leonese (WALZ), Central Iberian (CIZ) and Galicia Tras-os-Montes (Schistose Domain) Zones, together with the Ossa-Morena Zone of southern Iberia, preserve a more outboard tectonostratigraphy (Julivert *et al.*, 1972; Quesada, 1990; Ribeiro *et al.*, 1990; Perez Estaun *et al.*, 1991; Quesada, 1991; Martinez Catalan *et al.*, 1997; Gutiérrez-Marco, 1999; Marcos and Farias, 1999; Martínez Catalán *et al.*, 1999; Aramburu, 2002; Robardet, 2002; Robardet, 2003; Robardet and Gutiérrez-Marco, 2004) and constitute the orogenic hinterland. Boundaries between these zones are major Variscan thrust faults that were, in some cases, reactivated by extension in the aftermath of the Variscan Orogeny (Martinez Catalan *et al.*, 1997; Martinez Catalan *et al.*, 2003). Closure of the Rheic Ocean is recorded in northwest Iberia by deformation attributable to the Laurussia–Gondwana collision, referred to as the Variscan Orogeny, and by the emplacement of ophiolite interpreted as oceanic remnants thrust out of the Rheic suture between these continents.

The onset of continental collision began at *ca.* 365 Ma (Dallmeyer *et al.*, 1997) with initial subduction of the Gondwana margin below Laurussia. Deformation of the Gondwana passive margin succession migrated eastward in space and time and was caused by Laurussia overriding Gondwana. Convergence initially produced recumbent folds (D1) that verge and migrate from the suture towards the Cantabrian Arc. Continued shortening is thought to have led to the extensional collapse (D2) of the thickened orogenic hinterland (Viruete *et al.*, 1994; Arenas and Catalan, 2003; Pereira *et al.*, 2009) at *ca.* 320 Ma (Martinez Catalan *et al.*, 2009). Extensional collapse within the hinterland was coeval with the development of a non-metamorphic foreland fold-thrust belt within the Cantabrian Zone (Perez Estaun *et al.*, 1994). Immediately following ocean closure, an abrupt change in the stress field associated with Pangea amalgamation caused a dramatic 180° rotation of the Variscan Belt to produce the Ibero-Armorican Orocline.

Virtual Tour

The virtual tour of the Ibero-Armorican orocline presented herein is based on five animations, four 3D virtual reality representations and one film. These media types were chosen to illustrate the kinematic history and the mechanisms responsible for the arc’s development.

In this section we present two animations showing how paleomagnetic data (animation 1) and joint patterns (animation 2) have been used to constrain the timing of orocline development. Animations 3 and 4 are dynamic presentations of Late Carboniferous to Early Permian post-orogenic Iberian magmatism and the distribution of these intrusions within the developing orocline. Animation 5 shows an interpretation of the global-scale mechanisms that drove formation of the Ibero-Armorican orocline, and which involves the evolution and geometry of Pangea.

The virtual reality 3D video presents some of the results of analogue modelling experiments of oroclinal buckling carried out in the Deformation laboratory of Goethe University, Frankfurt (Germany). Video 1 is a film that synthesizes our experimental results, and which documents the evolution of our experiments

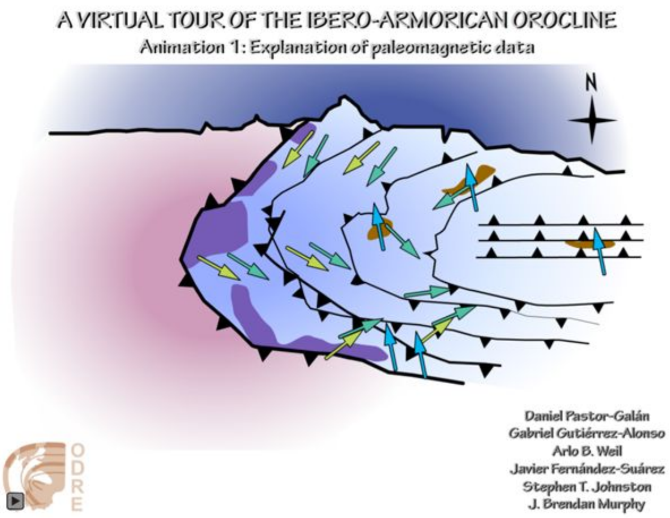
Kinematics and Timing

In this section two animations are presented that summarize the two methods used to constrain the timing of orocline development: paleomagnetic data (Animation 1) and joint pattern development (Animation 2) performed in the Cantabrian Arc, within the Cantabrian Zone (CZ).

The orocline model for the Ibero-Armorican arc relies on a wealth of paleomagnetic (e.g. Parés *et al.*, 1994; Weil *et al.*, 2000, 2001, 2010; Weil, 2006) and structural data (e.g. Julivert and Marcos, 1973; Alonso *et al.*, 2009; Pastor-Galán *et al.*, 2011; 2012a). It is characterized by early longitudinal thrust and folds generated by east-west shortening (in present coordinates) subsequently folded by a north-south shortening (e.g. Julivert and Marcos, 1973; Pastor-Galán *et al.*, 2012a). Based on paleomagnetic (van der Voo *et al.*, 1997; Weil *et al.*, 2000, 2001; 2010; Weil, 2006) and geological constraints (Pastor-Galán *et al.*, 2011; Gutiérrez-Alonso *et al.*, 2012), it is inferred that the orocline developed during a period of ~10 Ma in the uppermost Carboniferous (from 310 to 300 Ma). The orocline formation produced a N-S shortening that buckled the Variscan chain, a N-S directed thrust emplacement in the Cantabrian Arc (Merino-Tome *et al.*, 2009) and the reactivation of major structures like the Leon Fault (Alonso *et al.*, 2009).

Palaeomagnetic data (Animation 1) constrain the kinematics and timing of orocline formation. Rocks of the northern Gondwana foreland of the Variscan Belt in the Cantabrian Arc were remagnetized during and after early Variscan imbricate thrusting, yielding two syn-tectonic magnetizations. These magnetizations define two lineations that can be used to reconstruct the geometry of the arc at various times during its evolution (C and B magnetizations, Bashkirian and Moskovian in Animation 1; Hirt *et al.*, 1992; Parés *et al.*, 1994; Stewart, 1995a; Van der Voo *et al.*, 1997; Weil *et al.*, 2000, 2001). Unconformably overlying Early Permian continental strata along both limbs of the orocline preserve a primary magnetization that records no vertical-axis rotation, thus constraining the timing of vertical-axis rotations (eP magnetization, Permian in Animation 1; Weil *et al.*, 2010).

Figure - Animation 1.

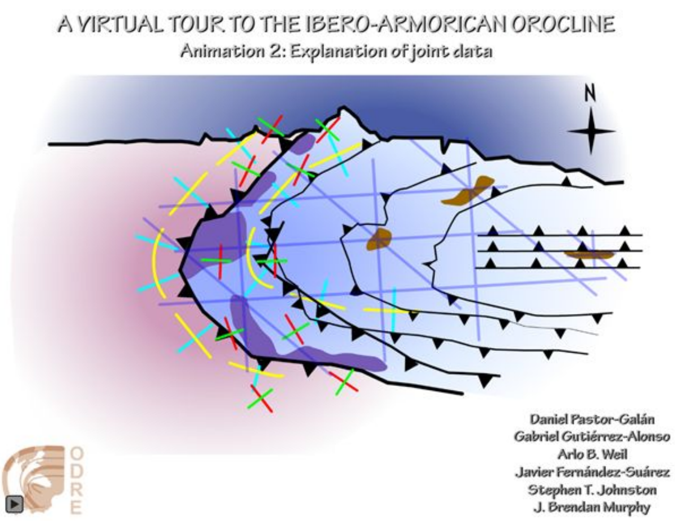


Interpretation of magnetic lineation acquisition prior to oroclinal buckling, and the subsequent clockwise rotation of the orocline's northern limb, and counter-clockwise rotation of its southern limb. The animation highlights the post-buckling Permian remagnetization showing no more vertical axis rotation and constraining the timing of oroclinal buckling. The constraints suggest that the orocline post-dates the acquisition of the syn-tectonic remagnetization of thrust imbricated strata at about 315 to 310 Ma, and predates deposition of the unconformably overlying Early Permian strata at about 299 Ma.

Animation 1 shows an interpretation of magnetic lineation acquisition prior to oroclinal buckling, and the subsequent clockwise rotation of the orocline’s northern limb, and counter-clockwise rotation of its southern limb. The animation highlights the post-buckling Permian remagnetization. The paleomagnetic constraints suggest that the orocline post-dates the acquisition of the syn-tectonic remagnetization of thrust imbricated strata at about 315 to 310 Ma, and predates deposition of the unconformably overlying Early Permian strata at ~299 Ma.

Joint sets (Animation 2) in the Cantabrian Arc Ibero-Armorican orocline are developed in strata that span the duration of Variscan orogenesis, including orocline formation (Pastor-Galán *et al.*, 2011; Gutiérrez-Alonso *et al.*, 2012). Joints in structurally imbricated strata that are continuously exposed around the orocline are related to thrust formation and oroclinal buckling (Moskovian in Animation 2; Pastor-Galán *et al.*, 2011). Syn-orogenic strata constrain thrust fault formation to have occurred by *ca.* 315-310 Ma (e.g., Alonso, 1987; Keller *et al.*, 2007; Merino-Tomé *et al.*, 2009). Two orthogonal joint sets are identified, one parallel to, and one 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 (Moskovian to Permian in Animation 2). Upper Pennsylvanian strata, deposited in continental basins, unconformably overlie the older, thrust imbricated strata (Kasimovian, 306 Ma in Animation 2). These strata have a younger orthogonal joint set that, when traced around the orocline, displaying a change in strike that defines about 60% of total arc curvature (Kasimovian to Permian in Animation 2). These sedimentary rocks are interpreted to have been deposited, and their joint sets developed, during orocline formation (Pastor-Galán al., 2011). Finally, joint sets in Early Permian strata that unconformably overlie the bent Variscan structures have joint sets that show no systematic change in orientation around the trace of the Cantabrian Arc, and are interpreted to post-date orocline formation (Permian, <299 Ma in Animation 2). Hence, these pre-, syn- and post-orocline sedimentary sequences and their joint sets indicate that the Cantabrian Arc formed after 315 Ma but prior to the Early Permian (pre- 299 Ma). This time frame is consistent with Upper Pennsylvanian strata (307 to 299 Ma) having been deposited during orocline formation.

Figure - Animation 2.



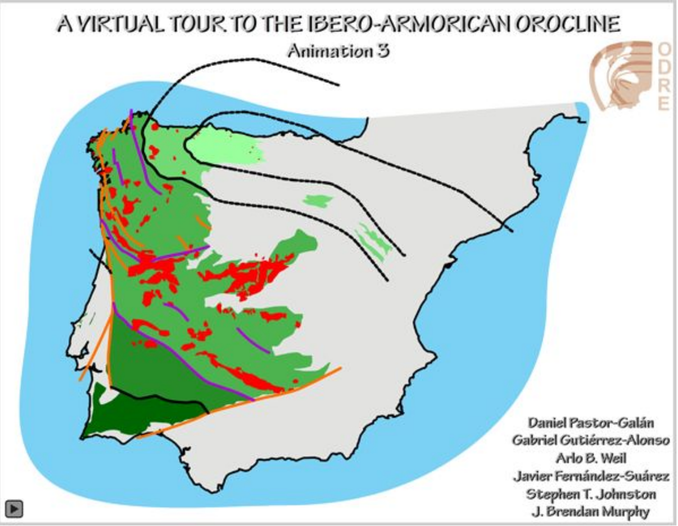
Interpretation of the formation of joint sets in the Cantabrian Arc. In pre-oroclinal buckling rocks, two orthogonal joint sets that traces the curvature of the arc are identified, one parallel to, and one normal to arc-parallel thrust traces and the axes of thrust-related fault-bend folds (Moskovian). Syn-orogenic strata constrain thrust fault formation to have occurred by *ca.* 315 - 310 Ma (e.g., Alonso, 1987; Keller *et al.*, 2007; Merino-Tomé *et al.*, 2009). Syn-orocline rocks (Upper Pennsylvanian strata, Kasimovian, 306Ma) have a younger orthogonal joint set that, when traced around the orocline, display a change in strike that defines about 60% of total arc curvature (Kasimovian to Permian). Finally, joint sets in Early Permian strata that unconformably overlie the bent Variscan structures have joint sets that show no systematic change in orientation around the trace of the Cantabrian Arc (Permian, <299Ma in Animation 2).

Lithospheric Response

Do oroclines evolve as thick-skinned, lithospheric-scale structures, or, are they thin-skinned features that terminate along crustal detachments? This fundamental question relates to the three dimensional geometry of oroclines and is one of the most challenging in understanding orocline development. Key insights are provided by comparing crustal and lithospheric mantle responses to orocline development. Significant syn-oroclinal magmatism is interpreted to reflect a lower-crustal and lithospheric mantle response to thick-skinned buckling (Gutiérrez-Alonso *et al.*, 2004, 2011a, 2011b, 2012). Synorogenic Variscan granitoid magmatism (345-315 Ma) accompanied the building and collapse of the Variscan orogenic belt (Fernández-Suárez *et al.*, 2000). Post-orogenic magmatism comprises intrusive and volcanic rocks emplaced between 310 and 285 Ma, and which are penecontemporaneous with, and slightly post-date, oroclinal buckling (Animation 3; Gutiérrez-Alonso *et al.* 2011b). The post-orogenic magmatic record consists of mantle- and crustal-derived melts that show systematic changes in age, spatial distribution, geochemistry and petrology, and includes voluminous foreland magmatism in the Ibero-Armorican oroclineCantabrian Arc (Gutiérrez-Alonso *et al.*, 2011b). Furthermore, the topographic response to this thermal event is recorded in the provenance and distribution of the Stephanian and Permian strata, and has been investigated through numerical modelling (Muñoz-Quijano and Gutiérrez-Alonso, 2007).

Animation 3 presents a thick-skinned interpretation of the Ibero-Armerican orocline, and illustrates the emplacement sequence of post-orogenic granitoids. Magmatism began in the orogenic hinterland with the intrusion of mantle-derived mafic melts from 310 to 305 Ma (Moskovian to Kasimovian in Animation 3). The early intruded mafic plutons in the hinterland are interpreted to result from decompressive mantle melting in the extending outer arc of the developing orocline. Thinning of the mantle lithosphere, and the resulting asthenospheric rise, would have elevated the geothermal gradient (see cross-section in the left side of Animation 3), which explains the subsequent melting of middle-upper crustal rocks, resulting in the intrusion of felsic magmas in the outer arc of the orocline between 305 and 295 Ma (Fernández-Suárez *et al.*, 2000, Gutiérrez-Alonso *et al.*, 2011b) (Kasimovian to Permian in Animation 3). 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. Magmatism in the inner arc (i.e. the foreland) began with the intrusion of mafic rocks and granitoids as well as widespread bimodal volcanism that continued until 292 Ma. This phase of magmatism was followed by felsic, crustal-derived leucogranite magmatism that continued for another 7 Ma (Gutiérrez-Alonso *et al.*, 2011b). The delayed onset of magmatism in the foreland is interpreted to reflect initial thickening of the lithospheric mantle in the Cantabrian Arc, forming an orogenic root that subsequently became gravitationally unstable. Delamination of the unstable root resulted in upwelling of hot asthenospheric mantle beneath the foreland, which explains the mantle-derived mafic magmatism and crustal melting (see cross-section in the left side of Animation 3).

Figure - Animation 3.



Thick-skinned interpretation of the Ibero-Armorican orocline illustrating the emplacement sequence of post-Variscan granitoids. Map-view in the right side display the timing of orocline formation and emplacement of granitoids while cross-section at the left side show the evolution of the lithosphere in depth. Thinning of the mantle lithosphere produce astenospheric upwelling resulting in the intrusion of mantle-derived mafic melts from 310 to 305 Ma (Moskovian to Kasimovian). This process elevated the thermal gradient explaining the subsequent melting of middle-upper crustal between 305 and 295 Ma (Kasimovian to Permian). On the other hand, initial thickening of the lithospheric mantle in the Cantabrian Arc, forming an orogenic root that subsequently became gravitationally unstable producing delamintion that resulted in upwelling of hot asthenospheric mantle beneath the foreland explain the magmatism in the inner arc of the orocline. This magmatism began with the intrusion of mafic rocks and granitoids from 300Ma. to 292Ma. This phase of magmatism was followed by crustal-derived magmatism from 292Ma to 285Ma.

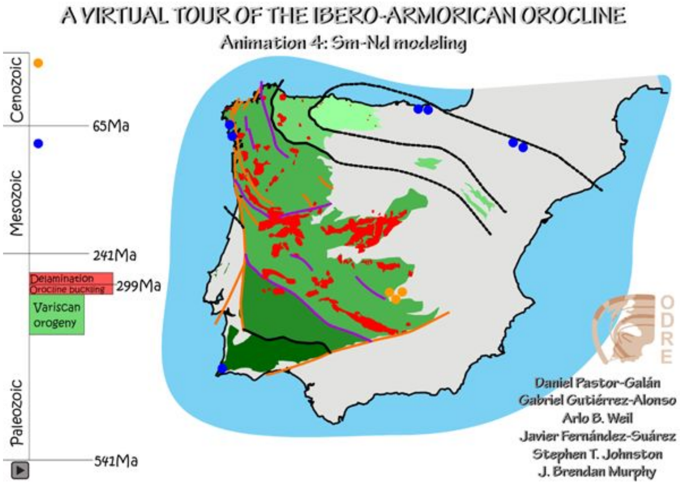
Sm/Nd isotope systematics of mantle-derived rocks provide further evidence of mantle lithosphere involvement during orocline development (Gutiérrez-Alonso *et al.*, 2011a; Ducea, 2011). Pre-oroclinal mantle-derived volcanic rocks indicate that the mantle lithosphere in NW

Iberia was emplaced, or metasomatized, at *ca.* 1.0 Ga while post-oroclinal mantle-derived magmatic rocks yield neodymium model ages (TDM) of *ca.* 0.3 Ga (Animation 4). This contrasting signature indicates that orocline formation was coeval with removal of an older mantle lithosphere that was replaced by a new, juvenile mantle lithosphere. 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 (Animation 4) (Gutiérrez-Alonso *et al.*, 2011a).

Animation 4 is a synthesis of the geochemical evolution of the pre-, syn- and post-orocline mantle-derived rocks and shows our interpretation of their formation. For clarity, the animation has been slightly modified from the figure from Gutiérrez-Alonso *et al.* (2011a) removing the plume related CAMP magmatic rocks.

Structural, paleomagnetic, geochronologic and geochemical data constrain mantle replacement and orocline formation to have been coeval, and is consistent with interpretation of the two processes as being genetically linked. We conclude that buckling of the Ibero-Armorican orocline involved the whole lithosphere (Gutiérrez-Alonso *et al.*, 2004).

Figure - Animation 4.



Synthesis of the geochemical evolution of the pre-, syn- and post-orocline mantle-derived rocks. Pre-oroclinal mantle-derived volcanic rocks indicate that the mantle lithosphere in NW Iberia was emplaced at *ca.* 1.0 Ga while post-oroclinal mantle-derived magmatic rocks yield neodymium model ages (TDM) of *ca.* 0.3 Ga. This contrasting signature indicates that orocline formation was coeval with removal of an older mantle lithosphere that was replaced by a new, juvenile mantle lithosphere.

Analogue Modelling

Thermo-mechanical analogue modelling provides insight into the feasibility of oroclines being lithospheric. We modelled lithospheric-scale buckling about a vertical-axis of rotation using plasticines with known contrasting rheological properties that were scaled to the mechanical properties of the crust, mantle lithosphere and the sub-lithospheric mantle (Pastor-Galán *et al.*, 2012b). A synthesis of the scaling parameters is shown in Table 1.

Table 1. Scaling parameters used in the modeling experiments

		Lower-crust	**Litho-spheric-mantle**	**Astheno-sphere**
ρ (kg/m^3)	Experi-ment	1250	1400	1250
	Nature	3100	3360	3100
	Scaling factor	0.4	0.41	0.4
η_{eff} (Pa·s)	Experi-ment	12900	57300	590
	Nature	1.13×10^{21}	5×10^{21}	5.15×10^{19}
	Scaling factor	1.146×10^{-17}	1.146×10^{-17}	1.146×10^{-17}
n	Experi-ment	7.8	4.37	3.41
	Nature	From 4 to 8	From 2 to 5	From 2 to 5

The modelling apparatus has a thermo-copper plate connected to an oven capable of imparting a vertical thermal gradient during experimental runs (Video 1). This thermal gradient allowed significant rheological change through time as Ibero-Armorican orocline is inferred to have happened during the formation of the Ibero-Armorican orocline. After buckling, the models were imaged using three-dimensional computer tomography (CT) using a 0.5 mm slice window and 0.5 mm slice depth, which rendered optimal resolution for the plasticines used in the experiments (3D images and Video 1).

The experimental set-up consisted of a 30x12x8 cm elongate model block (crust and lithospheric mantle and its underlying asthenospheric mantle), which was shortened into a buckle fold about a vertical axis (two examples view from a zenith camera shown in Video 1). Multiple experimental set-ups were used with variable strain rates and lithospheric thicknesses. 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 orocline outer arc. Thinning in the outer arc was accommodated by radial tension fractures, features that have not been observed in Iberia. Thickening in the inner arc was dependent upon initial lithosphere thickness. Thick mantle lithosphere further thickened through the formation of a tight, steeply plunging conical fold, whereas thin mantle-lithosphere thickened through formation of recumbent conical nappes (see 3D representations and Video 1). Although there are differences in detail, the first-order lithospheric-scale processes inferred to have taken place during the generation of the Ibero-Armorican orocline are well reproduced in the analogue experiments.

Virtual reality 3D representations were obtained using Computed Tomography (CT) analysis and show the morphology of the mantle lithosphere within the model. These 3D images were built in .pdf files and require Acrobat 9 or higher to view. Video 1 is a compendium film containing the development as well as the CT results of some of the experiments and the interpretation of the results.

Figure video.

Experimental set-up, developing and results of the analogue experiments. Results are 3D films obtained from the CT scanning of the samples. These results show the differences in lithospheric morphologies obtained. Click to download video (30MB, mp4 format).

3D representations

Three CT 3D representations built in .pdf files are presented. Feel free to move and observe the morphologies of the lithosphere obtained in the analogue modeling experiments.

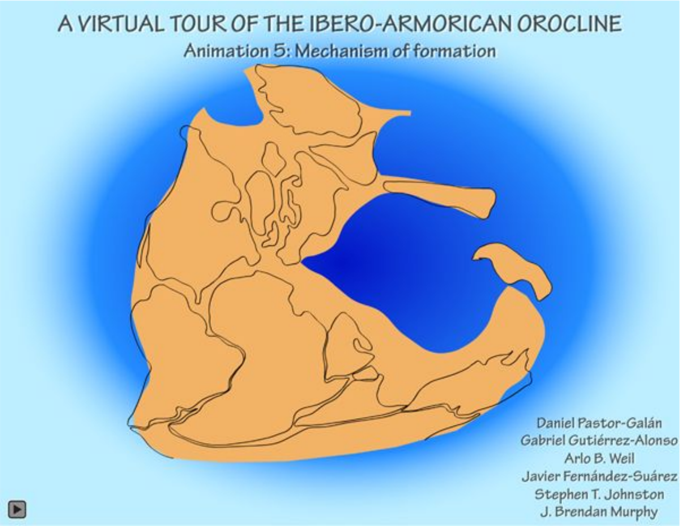
- Click to view first PDF
- Click to view second PDF
- Click to view third PDF

What caused the Ibero Amorican Orocline?

Available structural, geological, geochemical and geophysical data are consistent with the Ibero-Armorican orocline developing by buckling of an originally linear orogen (Weil *et al.* 2000, 2001, 2010; Gutiérrez-Alonso *et al.*, 2004, 2008, 2011a,b, Martinez-Catalan, 2011). Iberia was positioned close to the center of the Pangea supercontinent during orocline formation. The eastern margin of the supercontinent was characterized by a westward-tapering Paleo-Tethys oceanic embayment which apex was Iberia (first image in Animation 5). The Paleo-Tethys is inferred to have been characterized by an E-W trending mid-ocean ridge, a north-dipping subduction zone along its northern margin that descended beneath the Laurasian portion of Pangea, and a passive southern margin on the Gondwanan portion of Pangea. This palaeogeography (first image in Animation 5) is the basis for a potential explanation for orocline formation. Subduction of the mid-ocean ridge beneath the Laurasian margin of Pangea, would have resulted in “self-subduction” (Gutiérrez-Alonso *et al.*, 2008). After ridge subduction, oceanic lithosphere subducting beneath Laurasia would have been part of the Pangean plate, being attached to the opposing Gondwana passive margin of Pangea (Animation 5, 310 to 299 Ma). Because of the continuity of the oceanic lithosphere with the Gondwanan passive margin, slab pull due to northward subduction beneath the Laurasian margin of the Paleo-Tethys would have been transmitted into continental Pangea, resulting in a profound change in the Pangea stress regime (Animation 5, 310 to 299 Ma). The self-subduction strain would have been characterized by shortening and contraction within the inner region of Pangea that surrounded the western end of the Paleo-Tethys, and concomitant extension around the

Pangea periphery. In Animation 5, we suggest that the contraction within the inner tract of the Pangea superplate gave rise to the Ibero-Armorican orocline, explaining the lithospheric delamination, mantle replacement and the ensuing magmatic activity. In contrast, Late Paleozoic radial rift basins characterize the periphery of northern Pangea, supporting the idea of widespread extension around the edges of the superplate. Slab pull subsequently resulted in failure of the continental lithosphere along the northern Gondwana passive margin, creating a rift basin south of and parallel to the southern Tethys margin (Animation 5, 299 to 270 Ma). Self-subduction ended with the formation of the Neotethys mid-ocean ridge, which detached continental Pangea from the subducting slab (see cross-section in Animation 5). This final stage is likely recorded in the widespread Permian-Carboniferous unconformity in the continental basins of Europe.

Figure - Animation 5.



Schematic animation showing a simplified Pangea reconstruction and schematic lithospheric cross-sections through Paleo- and Neothethys oceans from 320Ma. to 270Ma. The animations shows the mechanism proposed for the formation of the Ibero-Armorican orocline: the self-subduction of Pangean global plate. The animation stops twice: at 310 Myr ago, at the starting of the orocline formation; at 299 Myr ago, when the orocline is finished.

Conclusions

Available structural, 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 complex oroclinal bending involving the whole lithosphere, highlighted by the formation of the Ibero-Armorican orocline.

Dynamic content is useful in illustrating complex geological processes like the formation of the Iberian-Armorican Orocline, which involved numerous different processes at different scales. Rigorously developed videos, animations, and 3D representations allow for more accurate models explaining the related geological processes. Dynamic content is a powerful development that facilitates the dissemination of science, not only in conferences and meetings but also in electronic journals.

Acknowledgements

This is a contribution to IGCP 497 and IGCP 597. Financial support for this work was supplied by Research Project ODRE II ("Oroclines and Delamination: Relations and Effects") No. CGL2009-1367 from the Spanish Ministry of Science and Innovation. JFS wishes to acknowledge financial support from project CONSOLIDER CGL2007-65338-C02-01/BTE by the Spanish ministry of Science and Technology. STJ thanks NSERC for a Discovery Grant. JBM acknowledges the continuing support of N.S.E.R.C., Canada. We acknowledge the critical reviews by G. Mohn and an anonymous reviewer, which helped to improve the final version of this paper.

References

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 approuch to continental drift. In: Carey, S.W. (Ed.), Continental Drift. A symposium. Hobart, Tasmania, p. 177- 355.

Ducea, M.N., 2011, Fingerprinting orogenic delamination: Geology, v. 39, p. 191-192.

Fernández-Suárez, J., Dunning, G.R., Jenner, G.A., & 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.

Franke, W., 2006, The Variscan Orogen in Central Europe: Construction and Collapse: Geological Society, London, Memoirs, v. 32, no. 1, p. 333–343, 10.1144/GSL.MEM.2006.032.01.20

Gutiérrez-Alonso, G., Fernández-Suárez, J., & Weil, A.B., 2004, Orocline triggered lithospheric delamination: Geological Society of America Special Paper, v. 383, p. 121-131.

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

Gutiérrez-Alonso, G., Fernandez-Suarez, J., Weil, A. B, Murphy, J. B, Nance, R.D., Corfu, F., Johnston, S. T., 2008. Self-subduction of the Pangean global plate. Nature Geoscience 1, 549-553.

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, 10.1130/G31468.1, p. 155-158

Gutiérrez-Alonso, G., Johnston, S.T., Weil, A.B., Pastor-Galán, D., Fernández-Suárez, J., 2012, Buckling an orogen: The Cantabrian Orocline. GSA Today, 10.1130/GSATG141A.1

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

Johnston, S.T., 2008, The Cordilleran Ribbon Continent of North America: Annual Review of Earth and Planetary Sciences, v. 36, no. 1, p. 495–530, 10.1146/annurev.earth.36.031207.124331

Johnston, S. T., 2001. The Great Alaskan Terrane Wreck: reconciliation of paleomagnetic and geological data in the northern Cordillera. Earth and Planetary Science Letters 193, 259-272.

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 Weil, A.B., and Sussman, A., editors; Curved Orogens. Geological Society of America, Denver, Special Paper 383, 225-236.

Johnston, S.T., 2008. The Cordilleran Ribbon Continent. Annual Reviews in Earth & Planetary Sciences, 36, 495-530.

Johnston, S.T., and Gutierrez-Alonso, G., 2010. The North American and Variscan Orogens: Contrasting interpretations of similar mountain systems. Gondwana Research, 17, 516-525.

Johnston, S. T., Mazzoli, S., 2009. The Calabrian Orocline: buckling of a previously more linear orogen. Geological Society, London, Special Publications 327, 113 -125.

Julivert, M., & 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.

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

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 Catalan, J. R. M., eds., 4-D Framework of Continental Crust, v. 200: Boulder, Geological Soc Amer Inc, 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, 131-156.

Martínez-Catalan, J.R.M., Arenas, R., Garcia, F.D., y Abati, J., 1997, Variscan accretionary complex of northwest Iberia: Terrane correlation and succession of tectonothermal events: Geology, v. 25, no. 12, p. 1103–1106.

Martínez-Catalán, J.R.M., 2002, Variscan-Appalachian dynamics: Geological Society of America.

Martínez Catalán, J.R. et al., 2007. Space and time in the tectonic evolution of the northwestern Iberian Massif. Implications for the comprehension of the Variscan belt. In: R.D. Hatcher Jr, M.P. Carlson, J.H. McBride and J.R. Martínez Catalán (Editors), 4-D framework of continental crust. Memoir. Geological Society of America, Boulder

Martínez Catalán, J.R., 2011, Are the oroclines of the Variscan belt related to late Variscan strike-slip tectonics?: Terra Nova, v. 00, p. 1-7.

Matte, P., 2001, The Variscan collage and orogeny (480-290 Ma) and the tectonic definition of the Armorica microplate: a review: Terra Nova, v. 13, no. 2, p. 122–128.

Merino-Tomé, O., Bahamonde, J.R., Colmenero, J.R., Heredia, N., Villa, E., & Farias, P., 2009. Emplacement of the Cuera and Picos de Europa imbrícate system at the Cantabrian Arc (Cantabrian Zone, N Spain); New precisions concerning the timing of arc closure. Geological Society of America Bulletin, v. 121, p. 729-751.

Merriam, D.F., 2009, A LOST ART: Geological Illustrations: GSA Today, v. 19, no. 11, p. 30-34.

Murphy, J.B., Gutierrez-Alonso, G., Nance, R.D., Fernandez-Suarez, J., Keppie, J.D., Quesada, C., Strachan, R.A., y Dostal, J., 2006, Origin of the Rheic Ocean: Rifting along a Neoproterozoic suture?: Geology, v. 34, no. 5, p. 325–328.

Parés, J.M., Van der voo, R., Stamatakos, J., and Perezestaun, A., 1994, Remagnetizations and postfolding oroclinal rotations in the cantabrian asturian arc, northern spain: Tectonics, v. 13, no. 6, p. 1461-1471.

Pastor-Galán, D., Gutierréz-Alonso, G., Weil, A.B., 2011, Orocline timing through joint analysis: Insights from the Ibero-Armorican Arc: Tectonophysics, v. 507, 1-4, p. 31-46.

Pastor-Galán, D, Gutiérrez-Alonso, G, Mulchrone, K.F., Huerta, P., 2012a, Conical folding in the core of an orocline. A geometric analysis from the Cantabrian Arc (Variscan Belt of NW Iberia). Journal of Structural Geology, 10.1016/j.jsg.2012.02.010

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

Pérez-Estaún, A., Bastida, F., Alonso, J.L., Marquinez, J., Aller, J., Álvarez -Marron, J. Marcos, A., & 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., & R.M. Shackleton, 1980, Rotation of the Iberian arc: Paleomagnetic results from north Spain: Earth and Planetary Science Letters, v. 50, p. 301-310.

Ries, A.C., y Shackleton, R.M., 1976, Patterns of Strain Variation in Arcuate Fold Belts: Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, v. 283, no. 1312, p. 281–288.

Robardet, M., 2003, The Armorica ‘microplate’: fact or fiction? Critical review of the concept and contradictory palaeobiogeographical data: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 195, no. 1–2, p. 125–148, 10.1016/S0031-0182(03)00305-5

Shaw, J., Johnston, S.T., Gutiérrez-Alonso, G., y Weil, A.B., 2012, Oroclines of the Variscan orogen of Iberia: Paleocurrent analysis and paleogeographic implications: Earth and Planetary Science Letters, v. 329–330, no. 0, p. 60–70, 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. 20079-20094.

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, 672 p., Clarendon, Oxford.

Sussman, A.J. & Weil, A.B., 2004. Orogenic curvature: Integrating paleomagnetic and structural analysis. Geol. Soc. Amer. Spec. Paper, 383, p. 1-271.

Toit, A.L du, 1937, Our wandering continents: an hypothesis of continental drifting: Oliver and Boyd.

Van der Voo, R., 2004. Paleomagnetism, oroclines, and growth of the continental crust. GSA Today, 14, Issue 12, 4-9.

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, no. B5, p. 10105-10119.

Van Staal, C.R., Dewey, J.F., Niocaill, C.M., y McKerrow, W.S., 1998, The Cambrian-Silurian Tectonic Evolution of the Northern Appalachians and British Caledonides: History of a Complex, West and Southwest Pacific-Type Segment of Iapetus: Geological Society, London, Special Publications, v. 143, no. 1, p. 197–242, 10.1144/GSL.SP.1998.143.01.17

Wegener, A., 1929, Die Entstehung der Kontinente und Ozeane: F. Vieweg & Sohn akt. ges., Braunschweig.

Weil, A.B. & Sussman, A., 2004. Classifying curved orogens based on timing relationships between structural development and vertical-axis rotations. Geological Society of America Special Paper, 383, 1-17.

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.

Weil, A.B., Van der Voo, R., & 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.

Weil, A.B., Van der Voo, R., van der Pluijm, B.A., & 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.

Wilson, J.T., 1949, THE ORIGIN OF CONTINENTS & PRECAMBRIAN HISTORY: Royal Soc.Canada Trans.,3rd Ser.v.43.