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Are the oroclines of the Variscan belt related to late Variscan strike-slip tectonics?

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ABSTRACT

Early Variscan structures and magnetic anomalies delineate four oroclines along the Variscan belt. The arcs bend the lithostratigraphic zones of the autochthon and the allochthonous terranes, which include ophiolites of the Rheic suture and units of Gondwanan derivation subducted on both sides of the Rheic Ocean. A transcurrent model dominated by right-lateral motion explains the genesis and evolution of the oroclines and a simple plate-tectonics scenario links late Variscan dextral strike-slip movements in the Variscides to a broad intracontinental shear zone, kinematically equivalent to a transform fault.

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Introduction

Four arcs characterize the Variscan belt: the relatively open Bohemian (BA) and Massif Central arcs (MCA), and the tight Ibero-Armorican (IAA) and Central Iberian arcs (CIA) (Argand, 1924; Du Toit, 1937; Carey, 1955; Bard *et al*., 1971; Perroud, 1986; Ribeiro *et al*., 1995; Tait *et al*., 1996; Franke and Zelazniewicz, 2002; Matte, 2001; Aerden, 2004; Martínez Catalán, 2010). The arcs fold the lithostratigraphic zones, as well as many Variscan structures and magnetic anomalies (Fig. 1), and are interpreted as oroclinal bends.

The Variscan belt is also characterized by orogen-parallel components, probably active during most of the continental convergence, and clearly demonstrated by large strike-slip shear zones developed at late orogenic stages (Gates *et al*., 1986; Hatcher, 2002; Martínez Catalán, 1990; Shelley and Bossière, 2000, 2002). Parallel components of plate convergence were considered responsible for terrane dispersion coeval with the formation of the IAA and more easterly arcs by Martínez Catalán *et al*. (2007), although no mechanism for arc formation was proposed. This contribution tries to integrate late Variscan transpression and orocline formation, and to explain the resulting geometry and its causes in terms of a simple plate-tectonics scenario.

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Geological setting

Figure 1 sketches the zonation, oroclines and main strike-slip shear zones of the Variscan belt. The Iberian autochthon, the central and northern domains of the Armorican Massif and several zones of the Bohemian Massif share stratigraphic and palaeotectonic similarities including a peri-Gondwanan origin and an internal domain with Early Ordovician magmatism related to crustal extension. (Cogné, 1974; Franke, 1989, 2000; Robardet *et al*., 1990; Young, 1990; Chantraine *et al*., 1994; Gutiérrez Marco *et al*., 1999, 2001; Eguíluz *et al*., 2000; Robardet, 2003; Robardet and Gutiérrez-Marco, 2004; Linnemann *et al*., 2004, 2008). The zone occupying a more distal and a more western position in the Gondwana margin shows also a strong Cadomian imprint in its Neoproterozoic series, and rift-related Early and Middle Cambrian magmatism.

Allochthonous terranes occur as remnants of a large nappe stack in north-west Iberia, southern Armorican Massif, French Massif Central, external crystalline massifs of the Alps, Maures Massif, Corsica, northern Sardinia, Vosges, Black Forest and Saxo-Thuringian Zone of the Bohemian Massif (references in Martínez Catalán *et al*., 2007). They include ophiolites of the Rheic Ocean and peri-Gondwanan units subducted at both sides of it. The references include a similar interpretation for the Moldanubian Zone and the Polish Sudetes, although an autochthonistic Andean interpretation has also been proposed for them (Schulmann *et al*., 2008, 2009).

The postulated single oceanic domain is paired with that of a single passive continental margin situated in northern Gondwana. The fact that all autochthonous zones formed a part of this margin explains the widely distributed evidence of the Late Ordovician (Hirnantian) Saharan Glaciation (Linnemann *et al*., 2004; von Raumer and Stampfli, 2008) and the continuous supply of the same zircon populations during the Palaeozoic, derived from the northern and western African cratons (Fernández-Suárez *et al*., 2002; Linnemann *et al*., 2004, 2008; Martínez Catalán *et al*., 2004; Gómez Barreiro *et al*., 2007; Díez Fernández *et al*., 2010; Bea *et al*., 2010).

Timing of Variscan oroclines

The formation of the IAA has been bracketed by palaeomagnetism between 304 and 295 Ma (Weil, 2006; Weil *et al*., 2010), but the age of the other arcs is less constrained. The CIA overprints D1 Variscan folds (360–335 Ma; Dallmeyer *et al*., 1997), so that its nucleation occurred later, either during emplacement of the allochthonous terranes (345–330 Ma; Dallmeyer *et al*., 1997; Martínez Catalán *et al*., 2007, 2009), during subsequent D2 extensional collapse (330–310 Ma; Díez Montes, 2007; Valverde-Vaquero *et al*., 2007) or during D3 folding (315–305 Ma; Capdevila and Vialette, 1970; Valle Aguado *et al*., 2005). But in any case, closure of the CIA was coeval with D3 folds, as their traces are often axial planar to the arc.

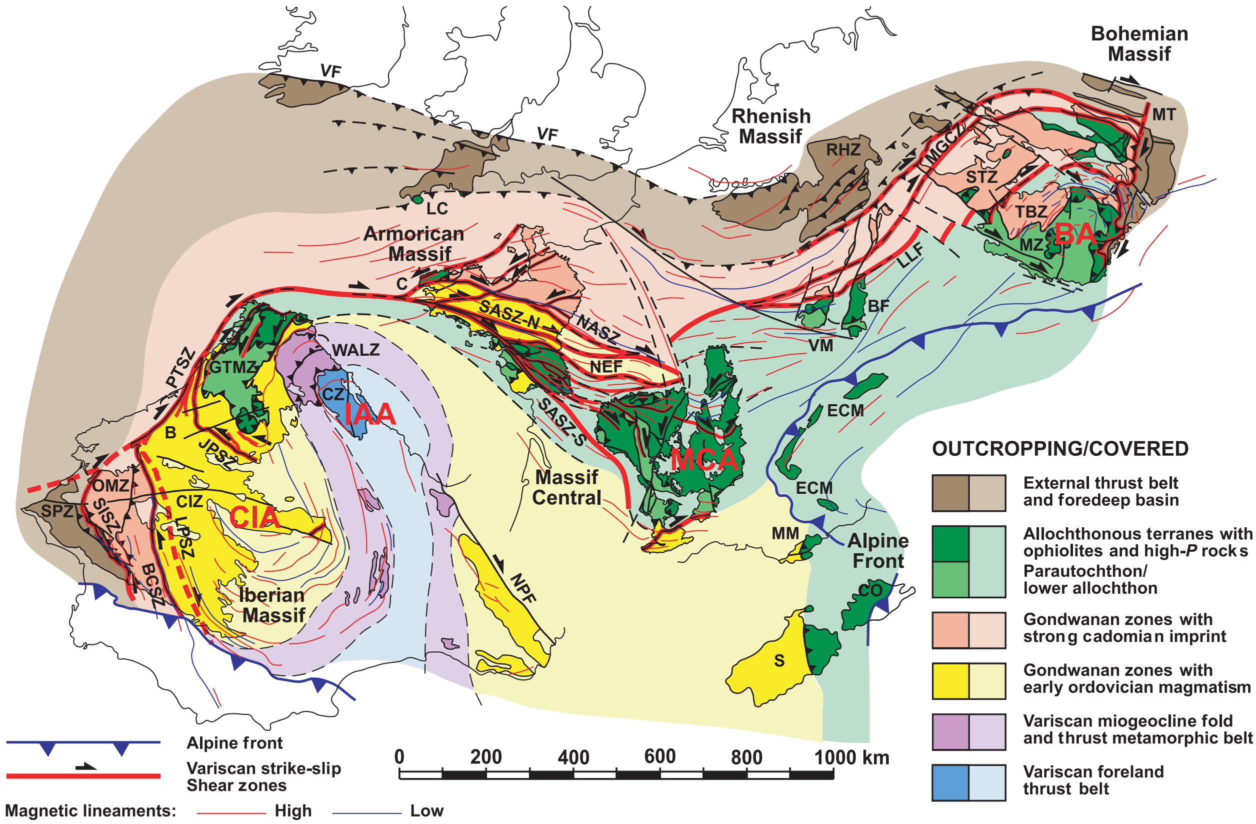

Fig. 1 Sketch of the Variscan belt, modified from Martínez Catalán *et al.* (2007). Magnetic data from the World Digital Magnetic Anomaly Map project (Maus *et al.*, 2007) and from Ardizone *et al.* (1989) for Spain, Galdeano *et al.* (1990) for France and Salansky (1995) for the Czech Republic. Arcs: BA, Bohemian; CIA, Central Iberian; IAA, Ibero-Armorican; MCA, Massif Central. Zones: CIZ, Central Iberian; CZ, Cantabrian; GTMZ, Galicia-Trás-os-Montes; MGCZ, Mid-German Crystalline; MZ, Moldanubian; OMZ, Ossa-Morena; RHZ, Rheno-Hercynian; SPZ, South Portuguese; STZ, Saxo-Thuringian; TBZ, Teplá-Barrandian; WALZ, West Asturian-Leonese. Shear zones and faults: BCSZ, Badajoz-Córdoba; JPSZ, Juzbado-Penalva; LLF, Layale-Lubine; LPSZ, Los Pedroches; MT, Moldanubian thrust; NASZ, North Armorican; NEF, Nort-sur-Erdre; NPF, North Pyrenean; PTSZ, Porto–Tomar; SASZ, South Armorican (N and S, northern and southern branches); SISZ, Southern Iberian; VF, Variscan front. Other: B, Buçaco; BF, Black Forest; C, Crozon; CO, Corsica; ECM, External crystalline massifs of the Alps; LC, Lizard Complex; MM, Maures Massif; S, Sardinia; VM, Vosges Massif.

D3 folds are linked to strike-slip shear zones (Iglesias Ponce de León and Choukroune, 1980), but the relationship between Variscan oroclines and strike-slip shear zones is complex, because not all shear zones were coeval and show different relationships with orocline development. Figure 1 shows folding of some shear zones by the MCA, and also that the southern branch of the South Armorican shear zone overprints previous dextral shear zones in the Armorican Massif. In Iberia, the Porto–Tomar shear zone cuts across the whole CIA and overprints all previous shear zones. Furthermore, the Porto–Tomar shear zone is folded by the IAA, but less tightly than the zones of the Iberian Massif, indicating that the CIA is older than or reached full development before the IAA. The Moldanubian thrust also overprints previous dextral shear zones folded by the BA, indicating a relatively late development, with the latest deformations in the area dated around 310 Ma (Schulmann *et al.*, 2008).

A transpressional model for late Variscan orocline formation

Current hypotheses of orocline development include slab rollback, typical of volcanic arcs and back-arc spreading, plastic indentation, buckling by parallel shortening and extrusion tectonics, which may be accompanied with slab retreat (Tapponnier *et al.*, 1986; Schellart and Lister, 2004). Buckling, as well as transpression, are thought to affect large strips of continental lithosphere known as ribbon continents (Johnston, 2001, 2008; Van der Voo, 2004).

A popular hypothesis for the origin of the IAA is a rigid-plastic indentation coeval with the main phases of the Variscan collision (Matte and Ribeiro, 1975; Matte, 1986), although buckling by parallel shortening has been proposed by Weil (2006). The CIA could be related to indentation during the emplacement of the northwest Iberian allochthon (Martínez Catalán, 1990), which occupies its core, but it is a subhorizontal thin sheet 15–20 km thick (Alcock *et al.*, 2009) that hardly can be viewed as a rigid indentor. An extruding wedge spreading laterally from the collision zone of two continents (Schellart and Lister, 2004) would be a more reasonable option for the nucleation of the CIA. Gneiss domes and D2 extensional detachments with a stretching lineation parallel to the axial trace of the arc (Escuder Viruete *et al*., 1994; Díez Balda *et al*., 1995; Díez Fernández, 2011), as well as large amounts of granites, occur beneath the allochthonous nappe stack and in the area surrounding it in the core of the CIA. All these facts point to significant crustal thickening, related to thrusting, but perhaps also to the arc itself. This would indicate synchronism, suggesting that extrusion tectonics might have triggered arc development. However, its tightness is better explained by D3 shortening, which is clearly associated with transcurrent shearing.

Strike-slip is a realistic option for oroclinal bending, as demonstrated by the South Island orocline in New Zealand, caused by dextral strike-slip motion of the Alpine fault (Norris *et al*., 1990; Hall *et al*., 2004). It was suggested by Perroud (1986) for the IAA and the Massif Central, and by Matte (2001) and Franke and Zelazniewicz (2002) for the Bohemian Massif, and is explored in what follows for the whole Variscan belt.

Figure 2 shows the feasibility of this assumption. It starts with the emplacement of the allochthonous terranes with a thrust front oblique to the zones in the autochthon (Fig. 2a), as deduced from the asymmetry of the allochthonous terranes in relation to the Central Iberian Zone (Fig. 1), and because in central Europe the allochthon cuts the more distal Gondwanan zone. Figure 2b,c shows the activity of a large strike-slip fault with stair-case trajectory and right-lateral motion, which fits the dominant parallel component of late Variscan wrench tectonics (Gates *et al*., 1986; Rolet *et al*., 1994; van Staal and De Roo, 1995; Shelley and Bossière, 2000, 2002; Franke and Zelazniewicz, 2002; Hatcher, 2002; Martínez Catalán *et al*., 2007).

Straights and bends in strike-slip faults are equivalent to ramps and flats in dip-slip faults, and originate at fault offsets (Woodcock and Fischer, 1986). A bend cutting across the Central Iberian Zone may have formed the CIA as a fault-bend or fault-propagation fold, perhaps helped by pinning at the western edge of the bend. The fault trajectory would have delineated a restraining bend (Crowell, 1974) that explains the arc and the contractional duplex of the Central Armorican Domain, which has Central Iberian affinities. Note that Fig. 2b,c explains the CIA essentially by transpression, but it might have been initiated by lateral extrusion of the wedge resulting from collision and the emplacement of the allochthonous terranes, being the result of combined extrusion and wrench tectonics.

A right-lateral shear zone hidden by Los Pedroches granitic lineament and the Culm basin (Aranguren *et al*., 1997) might represent the southern limit of the CIA, although not that of the Central Iberian Zone, whose

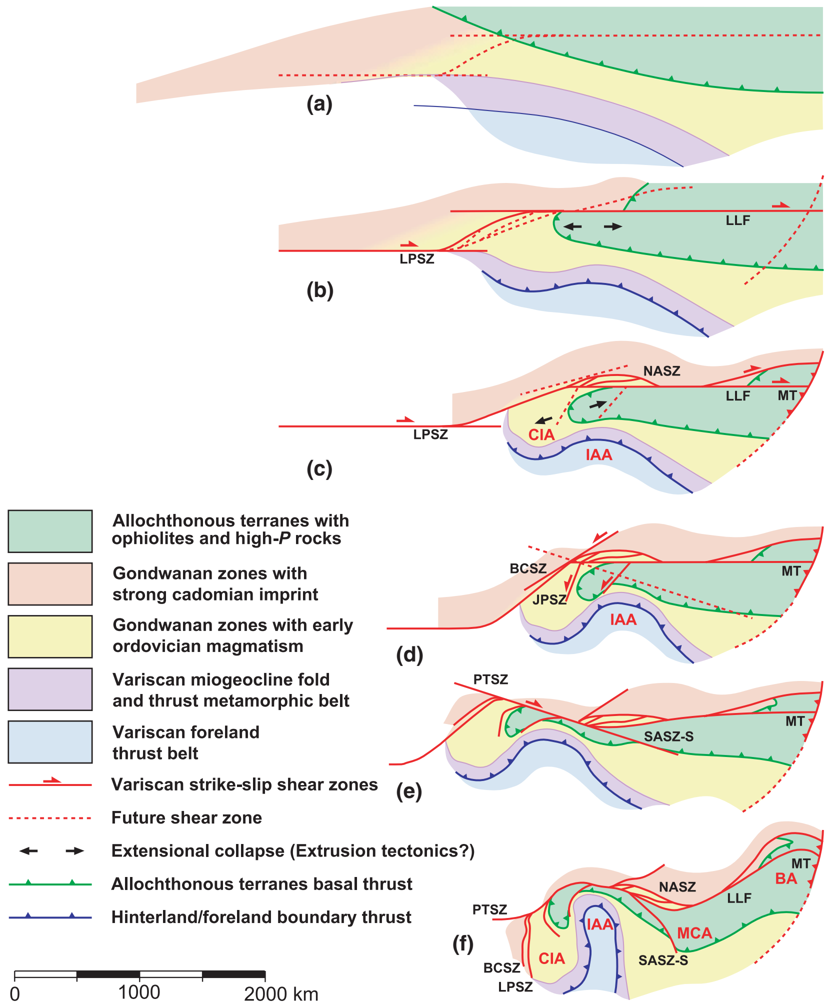

Fig. 2 Sketch of the proposed evolution of the Variscan belt during the middle and late Carboniferous, conditioned by the motion of right-lateral shear zones during Gondwana–Laurussia convergence. Dextral transpression explains the stratigraphic similarity between the Central Iberian and Central Armorican zones, and accounts for the original proximity of Buçaco (western Portugal) and Crozon (western Armorican Massif; B and C, Fig. 1), with identical Ordovician and Devonian sections (Henry *et al*., 1974; Paris and Robardet, 1977; Robardet *et al*., 1990; Young, 1990; Paris, 1998). Note that the Gondwanan zones with a strong Cadomian imprint occupy the relatively more distal position inside the continental margin (Robardet and Gutiérrez-Marco, 2004; Linnemann *et al*., 2008), but also a more western position, and that the boundary with the adjacent zone is assumed to be transitional. Abbreviations as in Fig. 1.

southern limit is the Badajoz–Córdoba shear zone (Burg *et al.*, 1981; Ribeiro *et al.*, 2007, 2009). Whether Los Pedroches shear zone binds to the south the CIA, or that limit corresponds to another dextral fault hidden by late left-lateral movements around the Badajoz–Córdoba shear zone, the main dextral fault would continue in central Europe by the North Armorican shear zone and the Layale-Lubine fault (Franke, 2000).

Figure 2d shows the activity of left-lateral shear zones cutting across the CIA, and kinematically equivalent to those bounding domino-style antithetic structures. Last motion along the Badajoz–Córdoba shear zone would have occurred at this stage, post-dating formation of the CIA and pre-dating the Porto–Tomar shear zone (Fig. 2e). The latter limits the CIA to the west and is believed to continue in the southern branch of the South Armorican shear zone, which cut across previous Armorican shear zones (Shelley and Bossière, 2002).

The Moldanubian thrust, with a dextral strike-slip component of more than 400 km (Franke and Zelazniewicz, 2002; 1000 km according to Matte, 2001), nearly limits the Variscan belt to the east. Figure 2f shows the development of the MCA and BA, and tightening of the IAA, linked to counterclockwise ductile rotation of the bounding shear zones to the west (Badajoz–Córdoba and Los Pedroches shear zones) and east (Moldanubian thrust), probably because their orientation was no longer appropriate to allow the blocks on both sides to glide.

Plate-tectonics framing

Arthaud and Matte (1977) interpreted late Variscan strike-slip faults as Riedel structures of types R (dextral) and R′ (sinistral) inside a right-lateral shear zone joining the Appalachians and the Urals (Fig. 3a). Its limits are subparallel to present geographical parallels in stable Europe, roughly following a small circle of the Earth surface, like transform faults. As it joined two destructive plate boundaries, it would be equivalent to an intracontinental transform with deformation distributed in a wide area.

This occurred at the waning stages of the Variscan cycle, when the crust was cold enough to show a brittle–ductile behaviour, with discrete shear zones binding rigid blocks. Shortly before, a more ductile behaviour of the same intracontinental structure may explain the large strike-slip shear zones and the formation of the arcs (Fig. 3b). The reference is the sector of an annulus whose northern part rotated counterclockwise with a relative displacement around 2000 km in the middle of the shear zone. Its limits would be equivalent to a couple of transform faults, with a restraining offset (Woodcock and Fischer, 1986) at the place of the Variscan belt. Riedel structures developed at each termination would have joined the other fault, giving rise to a pair of restraining bends.

The staircase trajectory might have developed the CIA and nucleated the IAA, whereas rotation of the restraining bends may have impeded slip, forcing them to evolve into contractional structures. The one in the west acted as a buttress, rotating the CIA and bending the previously nucleated arcs, whereas the one in the east, the Moldanubian thrust, evolved into a reverse fault and developed the BA. In the idealized reconstruction of Fig. 3b, the dark gray area represents a compressive bridge (Gamond, 1987) between two main en-échelon transforms that include the European Variscides.

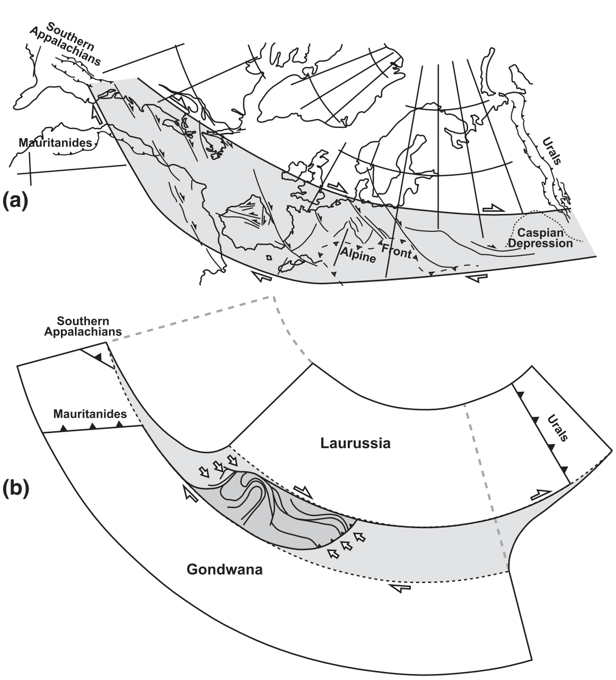

Fig. 3 (a) Late Variscan strike-slip faults in the Variscan belt interpreted as Riedel fractures in a right-lateral shear zone between the Appalachians and the Urals after Arthaud and Matte (1977). (b) Interpretation of the older, large strike-slip shear zones and oroclines of the Variscan belt as a transfer zone evolved into a compressive bridge between two transform faults representing the Laurussia–Gondwana plate boundary and joining the convergent boundaries of the Appalachians and the Urals. Same scale for (a) and (b).

Implications for the Variscan belt

Advances in the palaeogeography of the Variscan autochthon based on zircon age populations can be explained by dextral transpression. Although the Ossa-Morena, North Armorican and Saxo-Thuringian zones have affinities with the West African craton (Fernández-Suárez *et al.*, 2002; Linnemann *et al.*, 2004, 2008), the Central Iberian Zone reflects an intermediate position between it and more eastern regions of northern Africa, as indicated by Mesoproterozoic zircons derived from the Saharan craton and/or the Arabian–Nubian shield (Martínez

Catalán *et al*., 2004; Gómez Barreiro *et al*., 2007; Díez Fernández *et al*., 2010; Bea *et al*., 2010). The relative positions of the Central Iberian and Saxo-Thuringian zones are presently the opposite of those during the early Palaeozoic, and the inversion can be explained by right-lateral displacements of a few thousands of kilometres.

Orocline formation was facilitated by the peculiar rheology of the continental lithosphere. The arcs formed after thickening, during or after thermal relaxation and collapse, when the crust was recovering a normal thickness and was still hot and weak. Thermal models (Alcock *et al*., 2009) show that at the end of the Variscan cycle, the lower continental crust reached a high enough temperature to produce abundant anhydrous melts, and the mantle lithosphere was probably thin due to the raised isotherms. A thin lithosphere combined with a relatively hot crust favoured the development of the late Variscan oroclines, with internal deformation being accommodated by late folds, minor strike-slip shear zones and late extensional structures.

It has been proposed that the Variscan terranes formed a ribbon-like superterrane separated from Gondwana by the Palaeotethys (Stampfli and Borel, 2002; Stampfli *et al*., 2002; von Raumer *et al*., 2009). Although no ocean did exist south of Iberia by the late Carboniferous, when the Iberian oroclines were formed, the continental lithosphere could have been weakened by a suture, a continental rift or a Palaeotethyan transform fault. This would have favoured continental-scale transcurrence, and together with the northern strike-slip shear zones and perhaps the Rheno-Hercynian suture, would have bounded a weak, elongate continental strip prone to orocline development. The Variscan belt would then be another example of an orogenic strip sheared, imbricated and buckled by strike-slip tectonics, as the ones described by Johnston (2001, 2008), Sengör and Natal'in (2004) and Van der Voo (2004).

Conclusions

Transpression can explain the Variscan oroclines as developed in a broad shear zone kinematically equivalent to an intracontinental transform fault. A model is proposed that includes en-échelon, discrete shear zones with offsets connected by oblique segments that evolved into a compressive bridge. The distribution of autochthonous Gondwanan zones and the dispersed occurrence of ophiolites and subducted terranes related with a single oceanic realm are explained by intracontinental dextral transcurrence to the scale of the Variscan belt.

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