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Single subduction zone for the generation of Devonian ophiolites and high-P metamorphic belts of the Variscan Orogen (NW Iberia)

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ABSTRACT

Within the Variscan Orogen, Early Devonian and Late Devonian high-P belts separated by mid-Devonian ophiolites can be interpreted as having formed in a single subduction zone. Early Devonian convergence nucleated a Laurussia-dipping subduction zone from an inherited lithospheric neck (peri-Gondwanan Cambrian back-arc). Slab-retreat induced upper plate extension, mantle incursion and lower plate thermal softening, favoring slab-detachment within the lower plate and diapiric exhumation of deep-seated rocks through the overlying mantle up to relaminate the upper plate. Upper plate extension produced mid-Devonian suprasubduction ocean floor spreading (Devonian ophiolites), while further convergence resulted in plate coupling and intraoceanic ophiolite imbrication. Accretion of the remaining Cambrian ocean heralded Late Devonian subduction of inner sections of Gondwana across the same subduction zone and the underthrusting of mainland Gondwana (culmination of NW Iberian allochthonous pile). Oblique convergence favored lateral plate sliding, and explains the different lateral positions along Gondwana of terranes separated by Paleozoic ophiolites.

Keywords: Subduction; High-pressure rocks; Ophiolite; Suture Zone; Variscan Orogen

INTRODUCTION

Subduction zones are lithospheric breaks where downgoing slabs attain high-P (HP) conditions. Ocean spreading centers are sites where new oceanic crust is created. Ophiolites are tectonic slices of such crust and underlying mantle, and along with alkaline magmatism indicate sites of crustal extension and lithospheric boudinage (Gueguen et al., 1997).

HP metamorphic belts and ophiolites are closely related in most orogens. If the timing of subduction is similar to the timing of ophiolite emplacement, both can be linked in a subduction-trench complex via accretion and/or obduction (Wakabayashi and Dilek, 2003). Where this occurs, the age of subduction does not coincide with the protolith age of the ophiolites, and the ophiolites occur on top of the HP belt, or imbricated (scenario 1). Conversely, decoupling of subducting slabs may trigger upper plate extension and ocean floor spreading in back-arc and fore-arc regions (Stern, 2002). In this case, the timing of subduction is the same as the protolith age of the resulting ophiolites, and the ophiolites again occur on top of the HP belt (scenario 2).

The Variscan Orogen in NW Iberia presents a third scenario that differs from the regular cases cited above. NW Iberia contains the suture zone of a Devonian ocean basin (400-395 Ma; Arenas et al., 2014b), formed in a supra-subduction zone (Sánchez Martínez et al., 2007), that occurs as tectonic slices beneath HP rocks subducted at a similar, if slightly older age (420-390 Ma; Fernández-Suárez et al., 2007), and on top of HP rocks subducted at 380-370 Ma (Abati et al., 2010), shortly after the closure of the Devonian basin (395-380 Ma; Dallmeyer et al., 1997). Lithospheric extension so as to produce new ocean floor is unlikely for a lower plate during subduction, the upper plate being the most probable site for significant extension to occur. This way, NW Iberia represents a case where oceanic lithosphere thas was formed in the upper plate

(Devonian ophiolites) now occurs below sections of the lower plate that were subducted to mantle depths at the time when oceanic lithosphere was being created, i.e. when the upper plate was subjected to significant extension.

We present a model based on a compilation of multi-proxy regional data that explains the current arrangement of HP rocks and ophiolites in NW Iberia through the dynamics of an evolving, single subduction zone, as opposed to previous models that envisaged multiple subduction zones.

GEOLOGICAL SETTING AND PREVIOUS MODELS

The Variscan Orogen was formed from Late Paleozoic collision between Gondwana and Laurussia (Fig. 1). The existence of several suture zones has been attributed to accretion of peri-Gondwanan terranes during the closure of the intervening Rheic Ocean (*e.g.*, Kroner and Romer, 2013). A reworked suture zone between Gondwana and Laurussia is located along the boundary between the South-Portuguese and Rhenohercynian zones (Laurussia) and other sections of the orogen, which represent Gondwanan terranes (Díez Fernández et al., 2016). The Allochthonous Complexes of NW Iberia host another suture zone, and overlie a section (the Autochthon) that lacks sutures and represents mainland Gondwana (Fig. 1; Díez Fernández and Arenas, 2015). This allochthonous suture zone separates Gondwanan terranes, contains ophiolites and HP rocks (Arenas et al., 2016), and is the object of this study.

The Variscan suture zone in NW Iberia consists of two sets of continental terranes separated by ophiolites (summary in Fig. 2), all of which are thrust onto inner sections of Gondwana (Parautochthon and Autochthon). Tectonic transport for major thrusts is top-to-mainland Gondwana (Martínez Catalán et al., 2009). The upper continental terrane is divided into two parts; an Uppermost Allochthon on top, with mid-P and low- to high-T metamorphism, and an Upper Allochthon below, with Early-Middle Devonian HP metamorphism (peak-P at 420-390 Ma; Fernández-Suárez et al., 2007). Decompression of the latter was fast, occurred under HT conditions (extensive migmatization), and was completed in mid-Devonian times (397 Ma; Fernández-Suárez et al., 2007). The Upper Allochthon is now detached from the rest of the Devonian subducting slab to which it belonged, as it is thrust onto Devonian ophiolites formed coeval with its burial. Ophiolites occur below this HP-HT terrane and are divided into two groups. Protoliths of the Upper Ophiolites are Early-Mid Devonian (400-390 Ma) and were generated in a suprasubduction zone (Sánchez Martínez et al., 2007) that involved old continental/transitional crust (Arenas et al., 2014b). Protoliths of the Lower Ophiolites were formed in a Cambrian back-arc (Arenas et al., 2007). Beneath the ophiolites, at the base of the allochthonous pile, the Basal Allochthon represents a transitional back-arc section underlain by an Ediacaran series affected by Cambrian-Ordovician, arc-related magmatism (Díez Fernández et al., 2010). Metamorphism in the Basal Allochthon starts with a Late Devonian HP event (380-370 Ma; Abati et al., 2010).

There is consensus about the processes and timing that led to the tectonic piling in NW Iberia (Arenas et al., 2016). Devonian subduction polarity was Laurussia-directed, the Uppermost Allochthon being the upper plate during the whole process. Early-Mid Devonian subduction of the Upper Allochthon was followed by mid-Late Devonian imbrication of Devonian ophiolites and then subduction/accretion of Cambrian ophiolites. In the Late Devonian, the Basal Allochthon was buried through the same subduction zone as the Cambrian ophiolites, then acquiring its current basal position in the suture zone.

Previous models have proposed an explanation for the regional structure, metamorphism, timing of deformation, and paleogeography of the suture zone exposed in NW Iberia. Models can be grouped into: (i) those considering the suture to be that of the Rheic Ocean *s.l.* (Martínez Catalán et al., 2009); and (ii) those that consider it to be intra-Gondwanan (Arenas et al., 2014a). The first group considers the Uppermost and Upper Allochthons to be a coherent terrane that drifted from Gondwana in the Early Paleozoic and collided and subducted under Laurussia in the Early Devonian (HP metamorphism). In this scenario, Devonian ophiolites would have formed in intra-oceanic subduction zones that consumed the Rheic Ocean, which opened in the wake of the terrane that drifted in the Early Paleozoic (Sánchez Martínez et al., 2007). Ophiolite accretion resulted from closure of the remaining basins separating Gondwana and Laurussia after intraoceanic subduction. Subduction of the Basal Allochthon would mark the arrival of the most external section of Gondwana facing the Rheic Ocean after the Uppermost and Upper Allochthons had drifted away.

Data from the ophiolites, however, call into question the possibility that they represent true Rheic crust (Arenas et al., 2014b). Correlations across the Iberian Massif suggest the Uppermost Allochthon of NW Iberia is equivalent to the uppermost allochthons of SW Iberia (Fig. 1; Díez Fernández and Arenas, 2015). Here, paleontological and geochemical data do not support their separation from Gondwana during the Paleozoic (Linnemann et al., 2004), and place the Rheic suture along the eastern boundary of the South-Portuguese zone (Fig. 1).

The second group of models envisages a Devonian, multi-stage Gondwana-Laurussia collision (Arenas et al., 2014a; Franke et al., 2017). Devonian ophiolites represent basins that dissected the orogen (including HP belts) and were formed in the Early Devonian following a first collision. A second collision was heralded by ophiolite accretion along a new subduction zone. Burial of the Basal Allochthon marked the arrival of more internal sections of the Gondwana margin into the ongoing subduction zone.

PALEOGEOGRAPHY OF THE GONDWANA MARGIN IN IBERIA

Figure 3a shows a pre-Variscan paleogeography after qualitative restoration of Variscan thrusting in Iberia (Díez Fernández et al., 2016). Devonian ophiolites do not exist at this point. But for the rest of the allochthons, the depicted terranes represent a Cambrian-Ordovician back-arc, which make up a large-scale Paleozoic lithospheric neck across peri-Gondwana. The lack of prominent tectonic activity in this part of Gondwana between the Ordovician and Early Devonian, favors the hypothesis that this boudinage neck remained a regional feature of the margin until the onset of Variscan deformation.

The terranes that piled up in NW Iberia were distributed laterally along peri-Gondwana before the Variscan collision, the upper terranes being located westward and outboard across the margin relative to the underlying terranes (Gómez Barreiro et al., 2007). The largest lateral displacement between terranes within the allochthonous pile is inferred for the Basal and Uppermost Allochthons, which are interpreted to be fairly distant from one another along strike before collision (Díez Fernández et al., 2010).

SINGLE SUBDUCTION ZONE MODEL

The two sets of HP rocks of NW Iberia are separated by ophiolites, and the age of HP metamorphism is younger down structure, with a gap of some 15 m.y. between the age of HP metamorphism for each set (Fig. 2). This record has been regarded as evidence for two consecutive, yet different, subduction zones, regardless of the model used to explain the origin of the Devonian ophiolites. The polarity for both subduction zones is thought to be the same, and coincides with that of the subsequent underthrusting that drove the emplacement of the entire allochthonous package onto the Autochthon (Martínez Catalán et al., 2009). Variscan convergence in NW Iberia included a persistent dextral component from the Early Devonian through to the Late Carboniferous (Díez Fernández et al., 2016).

Any model attempting to explain the current arrangement of HP rocks and ophiolites in NW Iberia must consider the following data and inferences: (i) the HP rocks that occur on top of the Devonian ophiolites (Upper Allochthon) were subducted during the Early Devonian (420-390 Ma); (ii) subduction-exhumation of the Upper Allochthon is coeval to the opening of a supra-subduction ocean basin in the upper plate (400-395 Ma); (iii) the Upper Allochthon was detached from the downgoing slab at some point, and experienced significant heating (anatexis) after burial (Albert et al., 2012); (iv) the Early Devonian HP rocks of the Upper Allochthon are separated from the overlying Uppermost Allochthon by extensional detachments with diverse kinematics and affected by later folds (Gómez-Barreiro et al., 2007); (v) the Devonian ophiolites were thrust-imbricated in an intra-oceanic setting; (vi) the Cambrian ophiolites were subducted/accreted under the Devonian ophiolites; (vii) the HP rocks that occur below the ophiolites (Basal Allochthon) were subducted during the Late Devonian (380-370 Ma); and (viii) Variscan burial and exhumation of each of the tectonic slices that make the NW Iberian allochthons translates into rock assemblages with planar and linear fabrics that document penetrative and intense strain.

Progressive westward subduction/accretion within a single subduction zone could explain the Devonian record. However, extension (ocean basin inception) is needed in a region dominated by plate convergence. Arenas et al. (2014a) addressed this question by proposing the development of a pull-apart basin as a result of the oblique plate motion setting that governed Variscan tectonics. No further constraints were provided beyond the requirement for a blockage in Devonian subduction, full-plate rupture within the lower plate to create the ophiolites in a pull-apart basin, and inception of a new full-plate rupture to accommodate ophiolite accretion and subduction of the Basal Allochthon. However, the existence of a lithospheric break in this zone from the Early Devonian calls into question a model requiring two additional, consecutive breaks, since the existing one could have readily accommodated ongoing convergence.

Figure 3 shows a dextral, single subduction zone model for the Devonian evolution of NW Iberia. The model requires no blockage in subduction, confers a key role to slab-pull forces, acknowledges that the subduction hinge can converge, diverge or be stationary relative to the lower and upper plates (Doglioni et al., 2007), and exploits the pre-orogenic paleogeography of Gondwana (Fig. 3a). Early Devonian Gondwana-Laurussia convergence was resolved in NW Iberia by a subduction zone located between mainland Gondwana and a peripheral continental terrane, i.e. the Uppermost Allochthon (Fig. 3b; Díez Fernández et al., 2016). This subduction probably exploited a lithospheric neck inherited from a Cambrian back-arc. The lack of relics of oceanic crust (i.e., ophiolites) involved in Early Devonian subduction does not disprove the possible existence of other tracts of oceanic lithosphere equivalent to the ones observed in the Cambrian ophiolites, but separating the Upper from the Uppermost Allochthon within the Cambrian paleo-basin (Fig. 3a). If such oceanic crust did exist, it could have contributed to subduction initiation. In any event, subduction affected crust that increased in density (eclogitization) as burial progressed (HP metamorphism in Upper Allochthon), which contributed to slab-pull (Llana-Fúnez et al., 2004).

Early Devonian subduction was (dextral) oblique (Ábalos et al., 2003). Since no coeval deformation has been found in the upper plate in NW Iberia (Uppermost Allochthon), we think it reasonable that strain partitioning in this setting (Platt, 1993) produced trench-parallel translation of a (unstrained?) backstop in the upper plate along dextral strike-slip fault(s). However, a stationary subduction hinge relative to the upper and lower plates could have also limited the development of a pro-wedge or a retro-wedge, respectively.

The spreading center needed to form the Devonian ophiolites was located in the upper plate since ophiolite generation was coeval with ongoing subduction/exhumation through the subduction channel (Fernández-Suárez et al., 2007), and took place in a suprasubduction zone setting (Sánchez-Martínez et al., 2007), partly at the expense of continental crust (Arenas et al., 2014b). This seems incompatible with a stationary subduction hinge, which probably migrated away from the upper plate. Increasing slab-pull forces in the downgoing plate would foster slab-retreat and upper plate extension. This, in turn, would favor mantle incursion through the upper-lower plate interface to shallower depths, bringing overall thermal heating to the subduction system (Fig. 3c) (e.g., Sizova et al., 2019). Extension+heating would explain the exhumation of (colder) HP rocks back through a (hotter) subduction channel (Albert et al., 2012), as well as a general thermal softening of the lower plate. In a model of partitioned strain (Fig. 3c), the region between the backstop and trench tends to accommodate upper plate deformation. This region meets the criteria needed for the location of the Devonian ophiolites as it would be the site where mantle decompression and melting to feed the spreading centre was most effective, and also the place for new sections of the remaining Cambrian basin to be subducted/accreted below the remnants of the Devonian basin.

The present separation of rocks subducted in the Early Devonian from the rest of the downgoing slab can be explained by an increasing component of diapiric exhumation (Little et al., 2011) up and out of the subduction channel to relaminate the base of the overlying plate (Fig. 3d).

This process would account for the intense shearing registered by the Early Devonian HP rocks during decompression, and would be favored by continuous subduction, extensive partial melting (induced by mantle incursion?) and a thin upper plate (Maierová et al., 2018), all of which are parameters met by our case study (Fig. 3c) and suggested for the exhumation of HP rocks in other sections of the Variscan Orogen (e.g., Schulmann et al., 2014). Emplacement of the Early Devonian HP/HT rocks up to their current structural position was eventually driven by large-scale extensional detachments, which might have contributed to the development of a transient dome-like structure in the region. This structure seems lost to complex superimposed flattening, re-folding and faulting related to subsequent upper plate contraction (Gómez-Barreiro et al., 2007). The lack of Early Devonian HP rocks lying below Devonian ophiolites, combined with the north-directed thrusting responsible for the early imbrication of the latter (Goméz-Barreiro et al., 2010), is compatible with exhumation of the HP rocks occurring on the northern flank of the Devonian basin (Fig. 3d). This location corresponds to the expected site for a major strike-slip shear zone(s) accommodating strain partitioning (Figs. 3b-d). This shear zone would have provided a path to the upper plate for the Early Devonian HP rocks, which could have acquired their mid-P, orogen-parallel lineation (e.g. Abalos et al., 2003) during their transit along such a lithospheric fault.

The age of the main foliation in the Devonian ophiolites (395-380 Ma; Dallmeyer et al., 1997) indicates that the Devonian basin was sutured shortly after its inception. Imbrication of some Devonian ophiolites was intra-oceanic, as suggested by the development of metamorphic soles and certain petrofabrics (Gómez-Barreiro et al., 2010), thus supporting the failure of the mid-Devonian ridge(s) as a likely mechanism for initiating ophiolite imbrication (Fig. 3d-e). The young and buoyant nature of the Devonian oceanic lithosphere seems incompatible with spontaneous ridge collapse as the driving mechanism for the consumption of this basin. Thermal softening induced by mantle incursion plus vertical slab-pull in the lower plate could have promoted eventual slab break-off (Llana-Fúnez et al., 2004) and major tectonic changes (Figs. 3d-e). Fast exhumation and underplatting of the remaining subducting slab would increase plate coupling, while uplift would affect the upper plate, particularly the section closest to the trench (Magni et al., 2017). The ridge(s) of the Devonian basin would probably collapse upon such change. Mid-Late Devonian convergence would have taken advantage of a ridge's collapse to nucleate Gondwana-directed thrusts, through which young (buoyant) Devonian ophiolites (Fig. 3e) were eventually imbricated within a pro-wedge of a contracting upper plate (Martínez Catalán et al., 2009). Additionally, a switch to a converging state between the subduction hinge and upper plate could explain the contraction of the upper plate (Doglioni et al., 2007), and therefore the closure and imbrication of the oceanic lithosphere created in mid-Devonian times, even in the absence of slab break-off. However, slab detachment could explain both the absence of pre-Variscan ophiolites separating the Upper and Uppermost Allochthon as well as the gap in HP metamorphic ages between the rocks on top and below the ophiolites, since that particular record could have been lost to a piece of downgoing slab that never came back to surface.

The younger age of the main foliation of the Cambrian ophiolites (Dallmeyer et al., 1997) suggests that imbrication of Devonian oceanic lithosphere was replaced by subduction/accretion of transitional crust (Cambrian ophiolites; Fig. 3f), while the age of the HP metamorphism of the Basal Allochthon (380-370 Ma; Abati et al., 2010) as well as its structural position suggest that continued subduction brought more internal Gondwanan sections into the subduction zone (Fig. 3g). Upper plate extension (extensional detachments) during the Late Devonian (Gómez Barreiro et al., 2007) contributed to HP rock exhumation (Díez Fernández et al., 2011), probably in a context where slab-pull regained importance. As thicker continental crust reached the subduction zone, subduction was progressively replaced by flatter-lying underthrusting, culminating in the "allochthons on top of autochthons" structure of the Variscan Orogen (Fig. 3h).

Strain partitioning during Devonian oblique convergence also provides an explanation for the offset in the pre-orogenic paleogeographic positions of the upper (Uppermost Allochthon) and lower plate (Basal Allochthon and Autochthon) as the result of progressive lateral sliding of terranes along fault(s) related to ongoing dextral subduction (note progressive juxtaposition of white and green stars in map-view model in Figure 3).

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed.

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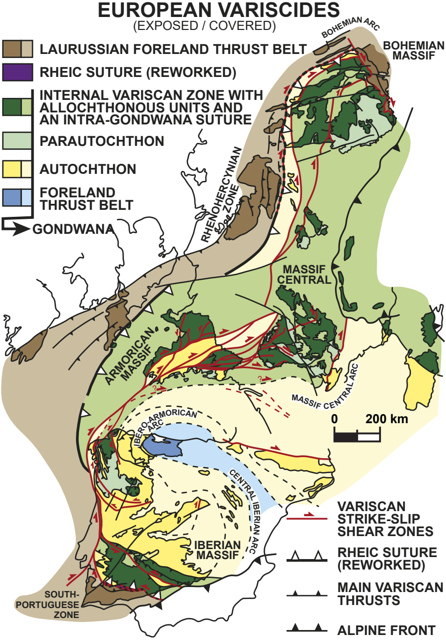
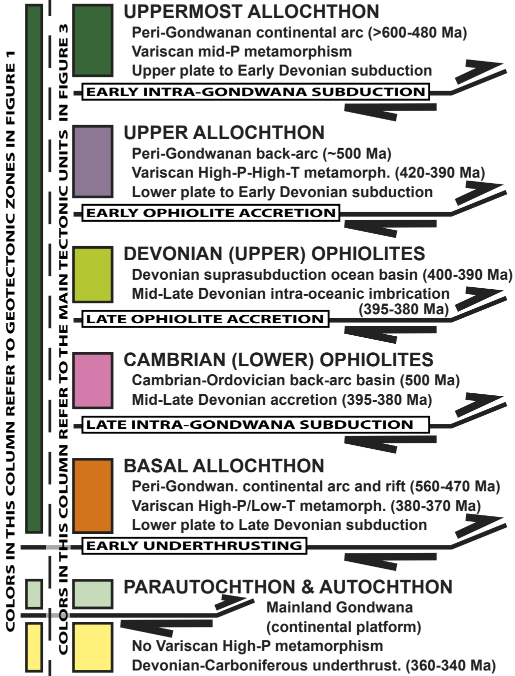
Figure Captions

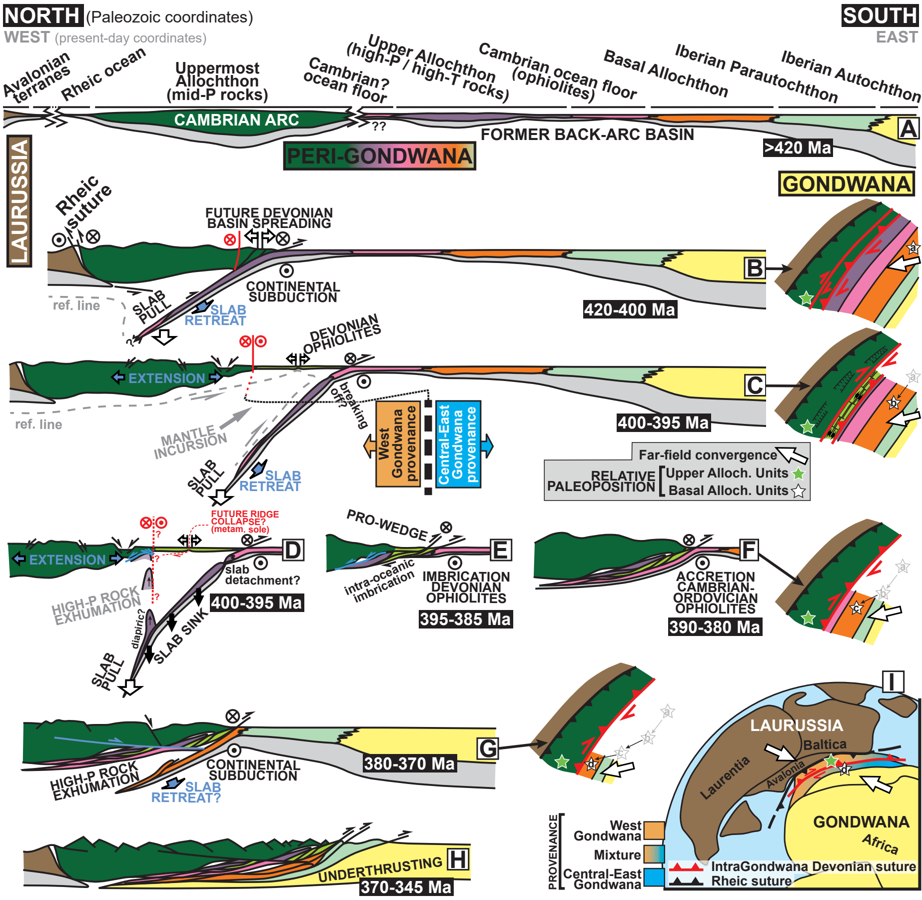
Figure 1: Zonation of the Variscan orogen after Díez Fernández and Arenas (2015).

Figure 2: Summary of main geological record for NW Iberian Allochthonous Complexes (see compilation by Arenas et al., 2016).

Figure 3: Single subduction zone model for the evolution of the intra-Gondwana suture of the Variscan Orogen. Main stages are represented by plate-scale cross-sections (left) and map-views (right), which also include a white star (lower plate) and a green star (upper plate) to trace normal and along-strike plate movements (vanished stars show former paleopositions).


EUROPEAN VARISCIDES
(EXPOSED / COVERED)
LAURUSSIAN FORELAND THRUST BELT
RHEIC SUTURE (REWORKED)
INTERNAL VARISCAN ZONE WITH ALLOCHTHONOUS UNITS AND AN INTRA-GONDWANA SUTURE
PARAUTOCHTHON
AUTOCHTHON
FORELAND THRUST BELT
GONDWANA
BOHEMIAN ARC
BOHEMIAN MASSIF
RHENOHERCYNIAN ZONE
MASSIF CENTRAL
ARMORICAN MASSIF
MASSIF CENTRAL ARC
IBERO-ARMORICAN ARC
CENTRAL IBERIAN ARC
IBERIAN MASSIF
SOUTH-PORTUGUESE ZONE
0
200 km
VARISCAN STRIKE-SLIP SHEAR ZONES
RHEIC SUTURE (REWORKED)
MAIN VARISCAN THRUSTS
ALPINE FRONT


COLORS IN THIS COLUMN REFER TO GEOTECTONIC ZONES IN FIGURE 1
COLORS IN THIS COLUMN REFER TO THE MAIN TECTONIC UNITS IN FIGURE 3
UPPERMOST ALLOCHTHON
Peri-Gondwanan continental arc (>600-480 Ma)
Variscan mid-P metamorphism
Upper plate to Early Devonian subduction
EARLY INTRA-GONDWANA SUBDUCTION
UPPER ALLOCHTHON
Peri-Gondwanan back-arc (~500 Ma)
Variscan High-P-High-T metamorph. (420-390 Ma)
Lower plate to Early Devonian subduction
EARLY OPHIOLITE ACCRETION
DEVONIAN (UPPER) OPHIOLITES
Devonian suprasubduction ocean basin (400-390 Ma)
Mid-Late Devonian intra-oceanic imbrication
(395-380 Ma)
LATE OPHIOLITE ACCRETION
CAMBRIAN (LOWER) OPHIOLITES
Cambrian-Ordovician back-arc basin (500 Ma)
Mid-Late Devonian accretion (395-380 Ma)
LATE INTRA-GONDWANA SUBDUCTION
BASAL ALLOCHTHON
Peri-Gondwan. continental arc and rift (560-470 Ma)
Variscan High-P/Low-T metamorph. (380-370 Ma)
Lower plate to Late Devonian subduction
EARLY UNDERTHRUSTING
PARAUTOCHTHON & AUTOCHTHON
Mainland Gondwana
(continental platform)
No Variscan High-P metamorphism
Devonian-Carboniferous underthrust. (360-340 Ma)



NORTH (Paleozoic coordinates)
WEST (present-day coordinates)
SOUTH
EAST
Avalonian terranes
Rheic ocean
Uppermost Allochthon (mid-P rocks)
Cambrian? ocean floor
Upper Allochthon (high-P / high-T rocks)
Cambrian ocean floor (ophiolites)
Basal Allochthon
Iberian Parautochthon
Iberian Autochthon
CAMBRIAN ARC
FORMER BACK-ARC BASIN
A
>420 Ma
PERI-GONDWANA
GONDWANA
LAURUSSIA
Rheic suture
FUTURE DEVONIAN BASIN SPREADING
CONTINENTAL SUBDUCTION
ref. line
SLAB PULL
SLAB RETREAT
B
420-400 Ma
DEVONIAN OPHIOLITES
EXTENSION
breaking off?
MANTLE INCURSION
SLAB PULL
SLAB RETREAT
West Gondwana provenance
Central-East Gondwana provenance
C
400-395 Ma
Far-field convergence
RELATIVE PALEOPOSITION
Upper Alloch. Units
Basal Alloch. Units
FUTURE RIDGE COLLAPSE? (metam. sole)
EXTENSION
D
slab detachment?
400-395 Ma
HIGH-P ROCK EXHUMATION
diapiric?
SLAB SINK
SLAB PULL
PRO-WEDGE
E
intra-oceanic imbrication
IMBRICATION DEVONIAN OPHIOLITES
395-385 Ma
F
ACCRETION CAMBRIAN-ORDOVICIAN OPHIOLITES
390-380 Ma
G
380-370 Ma
HIGH-P ROCK EXHUMATION
CONTINENTAL SUBDUCTION
SLAB RETREAT?
H
UNDERTHRUSTING
370-345 Ma
I
LAURUSSIA
Baltica
Laurentia
Avalonia
GONDWANA
Africa
PROVENANCE
West Gondwana
Mixture
Central-East Gondwana
IntraGondwana Devonian suture
Rheic suture