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Alpine, Variscan, eo-Variscan belts: comparison between hot and cold orogens from the examples of French segments

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Geodynamics of Continents and Oceans – A tribute to Jean Aubouin / *Géodynamique des continents et des océans – Hommage à Jean Aubouin*

Alpine, Variscan, eo-Variscan belts: comparison between hot and cold orogens from the examples of French segments

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Abstract. The Cenozoic Alpine, and Paleozoic Variscan and eo-Variscan collisional belts are compared in the framework of the Wilson cycle considering differences between cold and hot orogens. The W. Alps result of the opening and closure of the Liguro-Piemonte ocean, whereas the Paleozoic Eo-variscan and Variscan orogenies document multiple ocean openings and collisions in space and a polyorogenic history in time. Jurassic or Early Ordovician break-up of Pangea or Pannotia megacontinents led to the formation of passive continental margins, and the opening of Liguro-Piemonte, or Rheic, Tepla-Le Conquet, and Medio-European oceans, respectively. In Paleozoic or Mesozoic, microcontinents such as Apulia and Sesia or Armorica and Saxo-Thuringia were individualized. The oceanic convergence stage was associated with the development of arcs and back-arc basins in the Variscan belt but magmatic arcs are missing in the W. Alps, and inferred in the Eo-variscan one. Though the nappe stack is mainly developed in the subducted European or Gondwana crust in the western Alps and Eo-variscan cases, the Moldanubian nappes formed in the upper plate in the Variscan case. The Alpine and Variscan metamorphic evolutions occurred under ca. 8 °C/km and 30 °C/km gradients, respectively. During the late- to post-orogenic stages, all belts experienced "unthickening" accommodated by extensional tectonics, metamorphic retrogression, and intramontane basin opening. The importance of crustal melting, represented by migmatites, granites, and hydrothermal circulations in the Variscan and Eo-Variscan belts is the major difference with the W. Alpine one. The presence, or absence, of a previous Variscan or Cadomian continental basement might have also influenced the rheological behavior of the crust.

Keywords. Hot and cold orogens, Alpine, Variscan, Eo-variscan, Oceanic convergence, P–T paths, Crustal melting.

1. Introduction

Since the early times of plate tectonics, mountain building is viewed as a consequence of lithospheric evolution at converging plate boundaries, though intracontinental orogens may also develop in places where lithosphere has been previously thinned. The scenario formalized by the Wilson cycle [Wilson, 1966, Dewey and Bird, 1970, Burke and Dewey, 1974] is divided into several stages, namely: (i) *pre-orogenic* lithospheric divergence, characterized by ocean basin opening, between two continents, (ii) *orogenic* lithospheric convergence with successively oceanic subduction, continental subduction, and final collision when two continents contact, leaving a few relics of oceanic lithosphere as an ophiolitic suture, (iii) *late to post-orogenic stage* intracontinental deformation characterized by the disappearance of relief accommodated both by erosion and tectonics. Note that continental subduction is not a relevant criterion for collision, since this process may also occur in intracontinental belts and obduction chains in which the upper plate consists of oceanic lithosphere. This simple Wilson cycle model does not reflect the variety of collisional processes as plate velocities, lithosphere convergence vectors, slab dip, and crust internal rheology are not considered. The ophiolitic suture separating two collided continents may be erased by late tectonics, particularly by strike-slip movements. It became popular to distinguish "hot" and "cold" orogens due to their different thermal state, and crustal rheology [e.g. Vanderhaeghe, 2012, Jamieson and Beaumont, 2013, and references therein]. Such a distinction was already recognized as "hercynotype" and "alpinotype" orogens before the onset of plate tectonics [Zwart, 1967].

In Europe, the Cenozoic Alpine and Paleozoic Variscan belts are examples of collision orogens. However, in spite of similar architectural designs, each belt exhibits also its own peculiarities. This paper explores in which way the features of cold-narrow and large-hot orogens can be recognized in the Alpine and Variscan belts. Emphasis is placed on the tectonic, metamorphic and magmatic events occurring during each stage of the Wilson cycle. Due to space limitations, this comparison is restricted to the French segments of the two belts. A detailed description of the Alpine and Variscan belts is beyond the scope of this article [for details see Matte, 1986, Lagabrielle and Lemoine, 1997, Lemoine et al., 2000, Agard et al., 2002, Schmid et al., 2004, Agard and Lemoine, 2005, Faure et al., 2005, 2009, Ballèvre et al., 2009, Beltrando et al., 2010, Lardeaux, 2014a,b, Lardeaux et al., 2014; Table 1].

2. Tectonic zonation

At the scale of the peri-Mediterranean belts, the Alpine system (Figure 1) is related to the lithospheric convergence between Europe and Africa through the opening and closure of several intervening oceanic basins. The Variscan belt, including parts overlain by Meso-Cenozoic basins, and the Alpine basement, forms the substratum of Medio-Europa. The Alpine chain *stricto sensu* is geographically subdivided into the Western (French–Italian), Central (Swiss) and Eastern (Austrian) parts (Figures 2, 3). In the following, due to space constraints, only the Western Alps will be considered.

The W. Alpine belt results from the succession of the following events: (i) Pangea break-up, (ii) opening of the Liguro-Piemonte (LP) ocean, (iii) disappearance of the LP ocean by subduction below the Apulian margin, (iv) subduction of the European-derived Briançonnais continental ribbon below the Apulian margin, and (v) collision of the European continental margin with Apulia. Collision led to crustal thickening, nappe stacking, topographic rise, foreland and intramontane terrigenous basin formation, and exhumation of the deeply buried oceanic and continental crust.

Unlike this simple pattern of a single oceanic lithosphere jammed between two continental crusts, the Variscan belt exhibits a more complex tectonic framework. In the following, we deal with the Variscan segment that extends from SW England and Belgium to S. France. From North to South, it is subdivided into several lithotectonic domains, namely: (i) Northern foreland in Laurussia, (ii) Rheno-Hercynian, (iii) Saxo-Thuringian, (iv) Armorica microcontinent, (v) Moldanubian, and (vi) Southern foreland in Gondwana (Figure 4). In terms of plate tectonics, the domain boundaries correspond to ophiolitic sutures, even if ophiolites are not always well preserved due to subsequent tectonics. The Rheic, Tepla-Le Conquet, and Eo-variscan sutures separate continental blocks: Laurussia-Avalonia, Saxothuringia, Armorica, and N. Gondwana margin. The Western Alps result from a *single cycle* of lithosphere divergence and convergence from Late Triassic (ca. 225 Ma) to Miocene (ca. 10 Ma), during 215 My. In contrast, the Variscan orogen was produced by Eo-variscan and Variscan Paleozoic cycles of rifting and rewelding of Saxo-Thuringia, and Armorica microcontinents between Laurussia and Gondwana [e.g. Pin, 1990, Faure et al., 2005]. Consequently, the Variscan orogeny can be considered as the result of a *polycyclic* and *multi-collisional* process that developed during 260 Ma from Ediacaran (ca. 550 Ma) to Late Carboniferous (290 Ma), involving three oceanic basins, diachronously closed along three subduction zones.

Table 1. Main litho-tectonic elements of the W. Alps, Eo-variscan, and Variscan belts

	Western Alps	Devonian Eo-Variscan belt	Carboniferous Variscan belt
Ophiolites	Liguro-Piemonte ocean With (Monviso) or without (Chenaillet) metamorphism	Medio European ocean (Drain unit, Audierne)	Rheic & Tepla oceans Lizard klippe Le Conquet ophiolites
Subduction complex	Helminthoid flysch Schistes lustrés	Ile de Groix	Not exposed in France
Magmatic arc	Absent	Ligerian arc (inferred)	NE Morvan arc (Somme series) and Limousin tonalite line
Back-arc basin		Back-arc basin: (St-Georges/Loire unit)	Back-arc: Brévenne ophiolites
Basement nappe	Austroalpine nappe	Mauges nappe	Not documented in France Concealed below Paris basin
Ductile syn-metamorphic nappes	Schistes lustrés nappe Briançonnais nappes Penninic recumbent folds	Upper Gneiss Unit Lower Gneiss Unit	Para-autochthonous Unit thrust sheets
HP Metamorphism	Eclogite, Blue schist. Gradient 8 °C/km	Eclogites, HT Granulites Blue schist. Gradient 8–10 °C/km	Not documented in France
MP/MT metamorphism	Amphibolite facies	Barrovian metamorphism. 30 °C/km	Barrovian metamorphism. 30 °C/km
Non- or weakly metamorphic nappes	Dauphinois Fold-and-Thrust belt Helvetic recumbent folds	Not documented in France	North Fold-and-Thrust belt (Ardennes, SW England) South Fold-and-Thrust belt (Montagne Noire, Pyrenees)
Foreland basin	Helvetic molasse Po plain molasse	Absent	North foreland basin South Foreland basin
Intramontane basin	Some alpine valleys		Intramontane coal basins
Pre-orogenic magmatism	Triassic basalts, no Jurassic magmatism	Felsic and mafic volcanites Alkaline plutons	Brévenne back-arc basin Vosges klippen line
Syn-orogenic magmatism	Absent	Absent	Guéret biotite–cordierite granitic massif
Late to post orogenic magmatism	Rare (Biella, Adamello, Bergell in Central Alps)	Absent	Visean “Tufs Anthracifères” Monzogranites Two-mica granites Mg–K granites
Crustal melting	Rare (Lepontine dome)	Devonian Migmatite	Carboniferous Migmatite

3. The pre-orogenic stage

3.1. *Liguro-Piemonte ocean: Pangea breakup*

After the completion of the Variscan orogeny, a Permian-Triassic peneplain developed upon the eroded chain. A Carnian (ca. 225 Ma) early rifting episode occurred in the Briançonnais zone [Lemoine et al., 2000], and the Late Triassic alkaline magmatism recognized in the Helvetic zone is also ascribed to this rifting stage. In the External Crystalline massifs, east-facing normal faults coeval with syntectonic deposits in their hangingwalls document a middle to late Jurassic age for the main rifting stage, but contemporaneous magmatism is absent.

The Callovian–Oxfordian (ca. 165–155 Ma) opening age of the Liguro-Piemonte ocean is paleontologically and radiometrically constrained [Cordey and Bailly, 2007, Li et al., 2013]. Sedimentological and structural observations suggest that

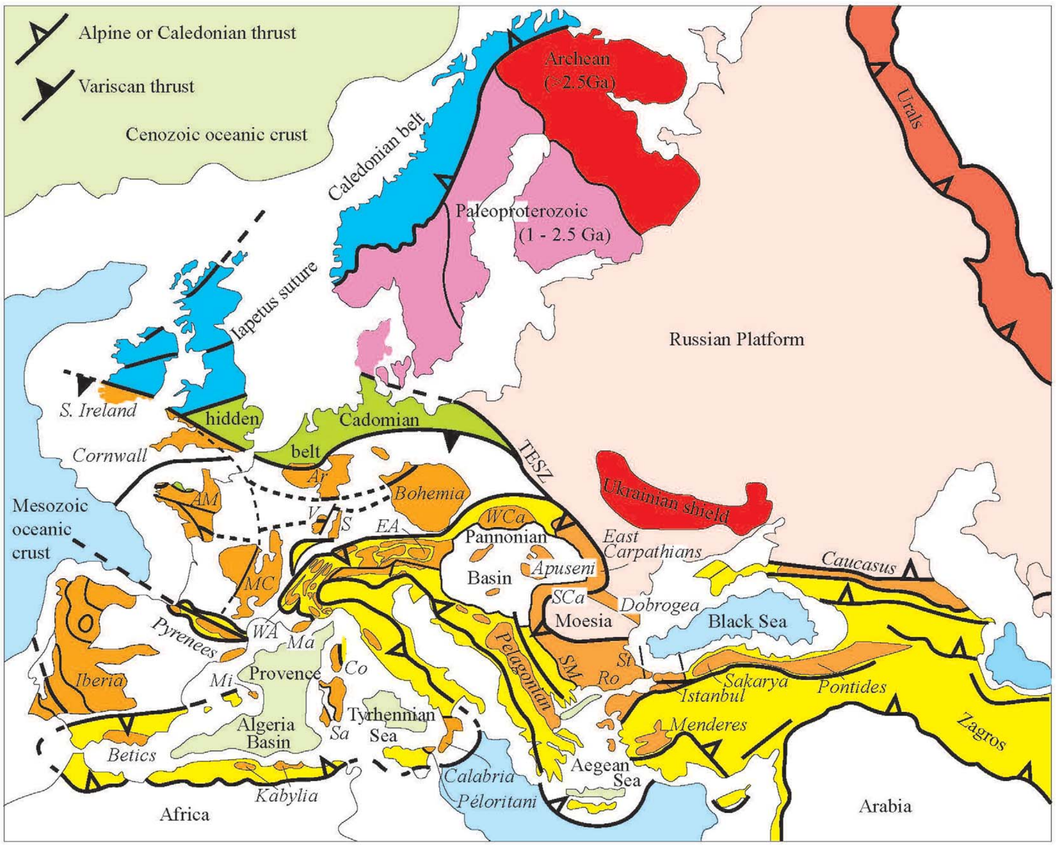

Figure 1. Distribution of the Alpine (yellow) and Variscan (brown) orogenic systems. The continuity of the Alpine belt is disrupted by the opening of the Neogene back-arc basins. The Variscan belt forms the basement of the Alpine one. The Neoproterozoic Cadomian belt is hidden by younger formations or reworked in the Variscan belt. Ar: Ardenne, Co: Corsica, Ma: Maures, AM: Armorican Massif, EA: Eastern Alps, MC: Massif Central, Mi: Minorca, Ro: Rhodope, S: Schwarzwald, Sa: Sardinia, SCa: South Carpathians, SM: Serbo-Macedonian, St: Strandja, TESZ: Trans-European Suture Zone, V: Vosges, WA: Western Alps, WCa: Western Carpathians.

the opening of the Liguro-Piemonte ocean was accommodated by east-dipping detachment faults [Lemoine et al., 1987, Lagabrielle and Lemoine, 1997]. At the Pangea scale, the Liguro-Piemonte ocean corresponds to a left-lateral pull-apart basin linking Central Atlantic and Tethys. Furthermore, in Central Alps, the Cretaceous Valaisan basin and the Bio Unit (Figure 3), similar to the Schistes Lustrés, can be also considered as other oceanic basins that isolated the Briançonnais and Sesia continental ribbons with respect to Europa and Apulia, respectively.

3.2. *Variscan rifting: Pannotia break-up*

In the Variscan belt, two rifting events occurred during the Ediacaran–Cambrian (ca. 550–540 Ma) and early Ordovician (480–465 Ma). The early one is represented by alkaline felsic magmatism exposed in Montagne Noire or in Normandy. This aborted rifting episode did not result in continental break-up. The main Variscan rifting took place in Early Ordovician. Alkaline or calcalkaline plutonism is widespread in the Moldanubian, Armorican and Saxothuringian domains [e.g. Ballèvre et al., 2012] Ordovician felsic volcanic-sedimentary “porphyroïd” formations are

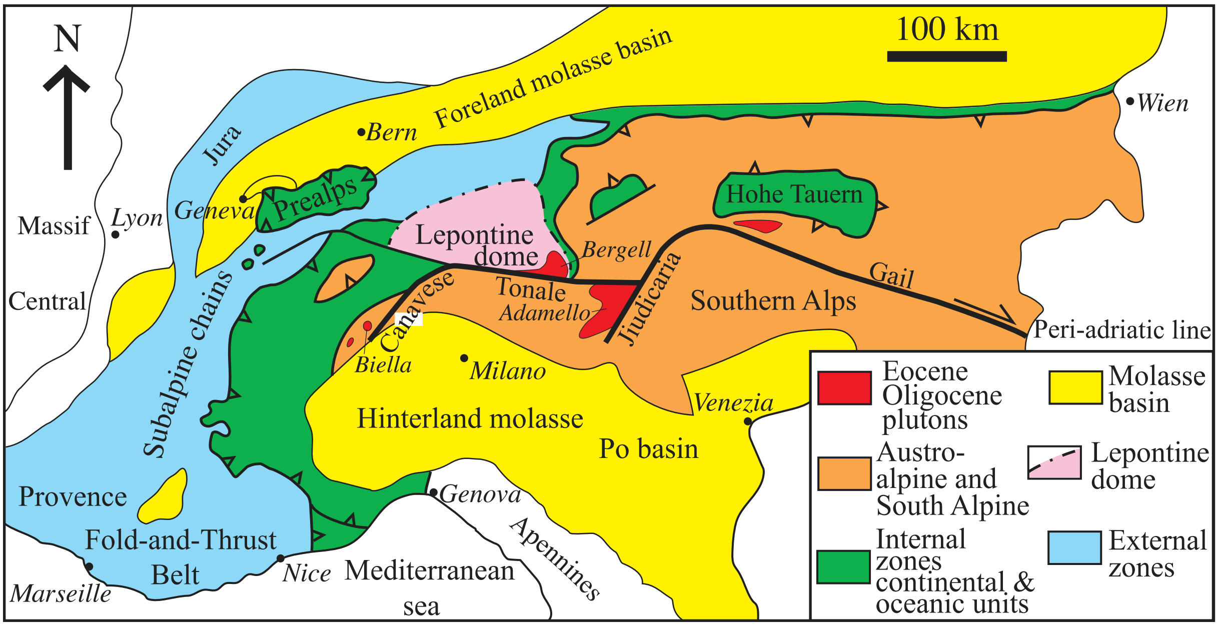

Figure 2. Tectonic map of the European Alps showing the European External, Internal, and Apulian domains, the foreland and hinterland molassic basins, and the Eocene–Oligocene plutons.

recognized in S. Brittany, Vendée, S. Limousin, Albigeois, Rouergue, Cévennes [Pouclet et al., 2017, Cousinié et al., 2022]. Alkaline basalts, dolerite, and gabbro are also locally exposed [Pin and Marini, 1993]. The Ordovician rifting is responsible for the development of "leptyno-amphibolite complexes" [e.g. Lardeaux, 2014a,b, and references therein]. This peculiar formation consists of cm- to m-scale alternations of rhyolitic lavas, tuffs, mafic lavas, dolerite, gabbro, and subordinate ultramafics. Such a bimodal magmatism commonly develops in areas where intense crustal thinning triggers mantle upwelling, and partial melting. The leptyno-amphibolite complex, exposed in both Upper and Lower Gneiss units but with different metamorphic grades, represents the ocean-continent transition. The Early Ordovician turbidites in Montagne Noire and Pyrenees are also ascribed to the Early Paleozoic rifting event.

In spite of the intense ductile deformation and metamorphism experienced by these formations, it is possible to unravel the passive continental margin from a proximal sediment-dominated part to a distal magmatic-dominated part (Figure 5). The true oceanic basin with ultramafics, gabbro, diabase, and oceanic sediments are only recognized along the Eo-Variscan suture in S. Brittany [Faure et al., 2005, 2008, Ballèvre et al., 2009]. In the French Massif Central, Early Paleozoic ophiolites are not exposed. The km-sized masses of serpentinite displayed in Decazeville, Central Limousin, or in Cantal are interpreted as pieces of infra-continental mantle. Deep oceanic sedimentary rocks (i.e. siliceous mudstone, radiolarian chert) are missing.

In Pyrenees, the Late Ordovician unconformity upon Early Ordovician rocks was regarded as an evidence for an Early Paleozoic Caledonian orogeny. However, it is now interpreted as a post-rift onlap upon the Early Ordovician rifting [Laumonier and Wiazemsky-Donzeau, 2014, Puddu et al., 2019]. In Central Brittany, the Early Ordovician syn-rift terrigenous deposits are unconformably covered by the Arenig Armorican sandstone post-rift deposit [Ballard et al., 1986]. In Ardenne, the Early Devonian unconformity upon Cambrian–Ordovician turbidites, previously considered as an evidence for a Caledonian event, is now interpreted as the mark of the post-rift event [Sintubin et al., 2009].

In summary, the Variscan pre-orogenic stage led to the development of three continental stripes, from South to North in the present coordinates: Armorica, Saxo-Thuringia, and Avalonia. These microcontinents were separated by oceanic basins, called Medio-European, Le Conquet-Tepla, and Rheic oceans. They drifted from the N. Gondwana margin, represented by the S. part of the Armorican Massif, Massif Central, Pyrenees, and S. Vosges. An important difference with the W. Alps already appears at this stage, the Gondwana passive continental margin was the place of a widespread magmatism whereas syn-rift magmatism is absent in the Alpine one.

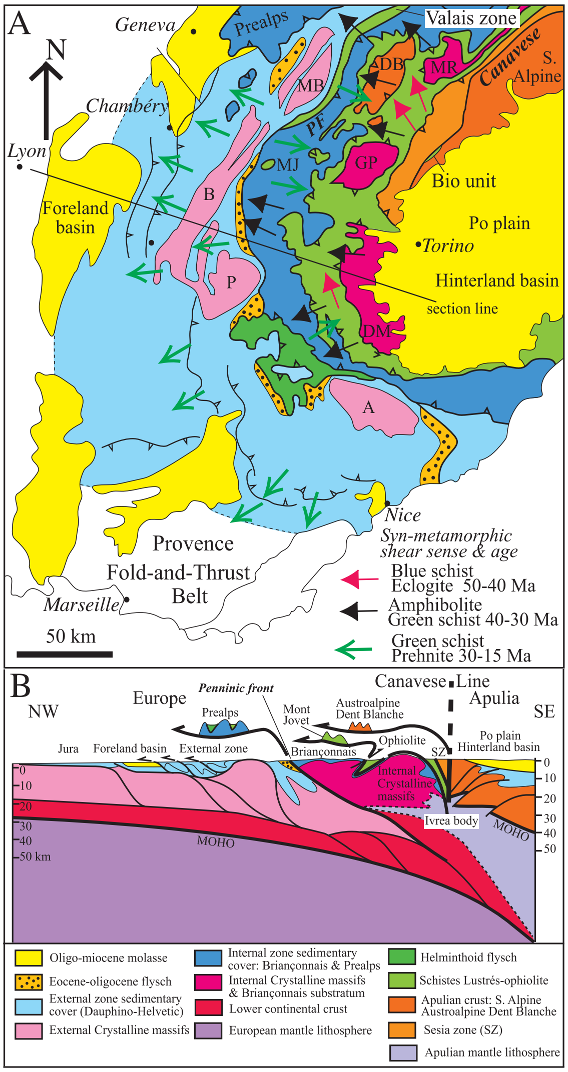

Figure 3. (A) Tectonic map of the Western Alps with the sense of synmetamorphic ductile shearing. MB: Mont Blanc, B: Belledonne, P: Pelvoux, A: Argentera, GP: Gran Paradiso, DM: Dora Maira, DB: Dent Blanche, MR: Monte Rosa, PF: Penninic Front, MJ: Mont Jovet [modified from Lemoine et al., 2000, Agard and Lemoine, 2005]. (B) Schematic crustal-scale cross section (located in the map) of the Western Alps [modified from Roure et al., 1989]. The Internal klippes of Prealps, Mont-Jovet, and Dent Blanche, exposed in the northern part of the Western Alps are projected on the line of section.

4. The oceanic convergence stage

4.1. *Western Alps: Liguro-Piemonte Ocean closure*

The Alpine orogeny started with the closure of the Liguro-Piemonte ocean, accommodated by eastward subduction below Apulia (Figure 6A). The Alpine oceanic convergence is at variance with the Wilson scheme since the magmatic arc is lacking, and even arc-sourced detrital Cretaceous zircons are absent in the flysch deposits [e.g. Chu et al., 2016]. The Late Cretaceous Helminthoid flysch is considered as a trench-fill deposit that escaped deep-seated subduction but was thrust in Middle Eocene upon the Briançonnais zone. In contrast, the Schistes Lustrés-with-ophiolites nappe is interpreted as the metamorphic part of the subducted material. The HP/LT metamorphism is well documented [Agard et al., 2002, Lardeaux, 2014a; Figure 7]. Two types of ophiolites are distinguished: the weakly deformed ones (e.g. Chenaillet) that probably belong to the upper plate, and the ophiolite thrust sheets that record a HP/LT metamorphism (e.g. Monviso) attached to the subducting plate.

4.2. *The Eo-Variscan belt: Medio-European ocean closure*

In France, Eo-Variscan ophiolites formed in the Medio-European ocean are exposed only in S. Brittany, along the Nort-sur-Erdre fault, and in the Audierne bay. In the former area, the mafic-ultramafic association and sedimentary rocks, devoid of HP metamorphism, are ascribed to the upper plate (Figure 6). They overthrust gneiss and migmatites of the Champtoceaux complex, correlated to the Massif

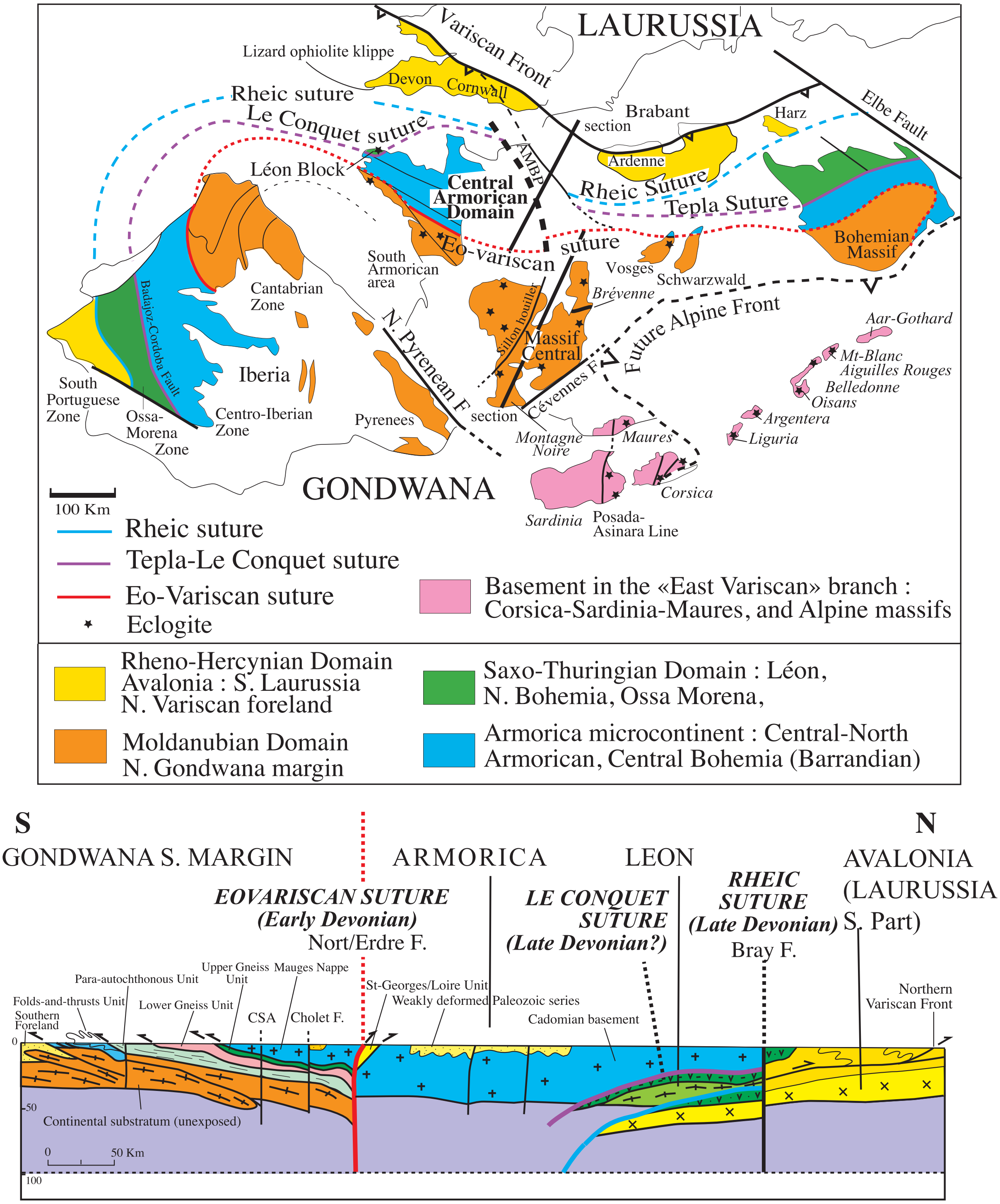

Figure 4. Structural map and crustal-scale cross section (located in the map) of the Variscan belt of Western Europe [modified from Matte, 1986, Faure and Ferrière, 2022].

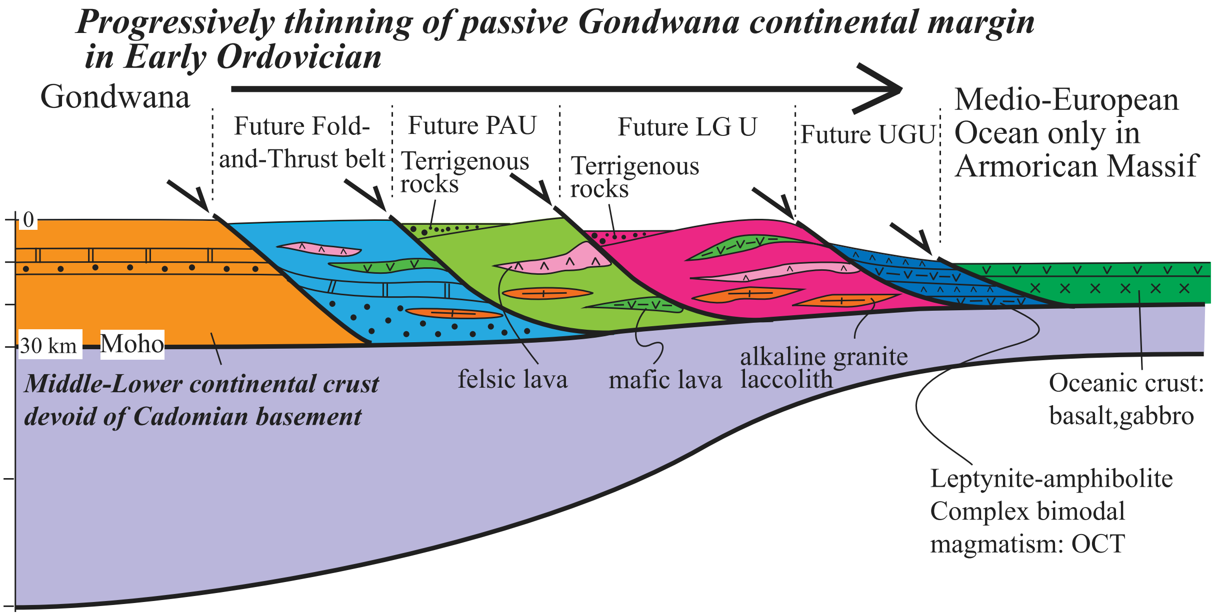

Figure 5. Simplified reconstruction of the Gondwana passive continental margin in Early Ordovician. PAU: Para-autochthonous Unit, LGU: Lower Gneiss Unit, UGU: Upper Gneiss Unit. The UGU will experience a high to ultra-high pressure metamorphism during continental subduction.

Central Upper Gneiss Unit. In France, blueschists are rare, the largest exposures are found in S. Brittany (Ile de Groix) where metapelites and metabasites are interpreted as formed in an accretionary complex [Bosse et al., 2005, Ballèvre et al., 2009; Figure 7]. The architecture of the Eo-variscan belt documents a stack of nappes similar to the Alpine one (Figure 4). The ophiolitic nappe is tectonically overlain by the Mauges nappe with Neoproterozoic metamorphic rocks already deformed during the Cadomian orogeny, and unconformably covered by Early Paleozoic sedimentary rocks. The disappearance of the Medio-European ocean was accommodated by a northward subduction below Armorica. The oceanic convergence setting has to take into account also the St-Georges-sur-Loire Unit located in the Armorica block immediately north of the Eo-variscan suture. This block-in-matrix unit is interpreted as a back-arc basin, north of a possible magmatic arc subducted during the Armorica–Gondwana convergence [Figure 6B; Cartier and Faure, 2004, Faure et al., 2008, Ducassou et al., 2011].

4.3. *The Variscan belt: Rheic and Tepla oceans closure*

The Carboniferous Variscan orogeny corresponds to the closure of the Rheic and Tepla-Le Conquet oceans with ophiolitic sutures located in the English Channel and in NW Brittany, respectively (Figures 4, 6C). In the Léon (i.e. Saxo-Thuringian microcontinent), the top-to-the-North synmetamorphic ductile shearing argues for a S-directed subduction [Rolet et al., 1994, Faure et al., 2010]. Another evidence for southward subduction is found in the NE Massif Central (Morvan area). There, basalt, andesite, volcanic-sedimentary rocks and massive sulfide deposits support a Late Devonian magmatic arc [Delfour, 1989, Faure et al., 2005]. The Brévenne ophiolites represent the back-arc basin opened during the southward subduction of the Tepla ocean. Between the Ardennes and Vosges, geophysical data also document south dipping Rheic and Tepla sutures [Edel and Schulmann, 2009]. The Devonian diorite-granodiorite massifs of the Limousin “tonalite line” [Didier and Lameyre, 1969, Peiffer, 1986] are also interpreted as an evidence for arc plutonism.

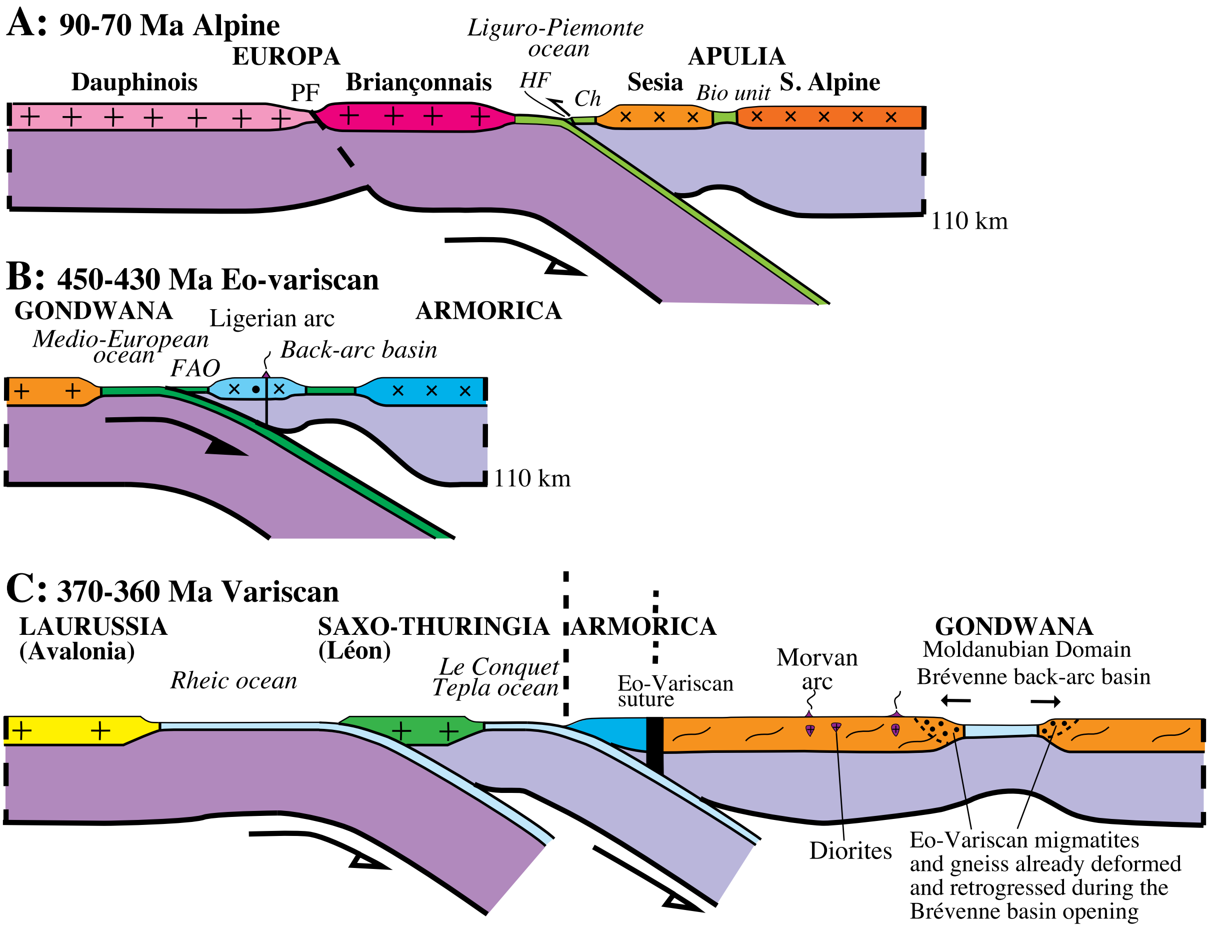

Figure 6. Compared geodynamic cross sections during the Alpine (A), Eo-variscan (B), and Variscan (C) convergence stage showing the diversity of subduction with forearc ophiolites (FAO), magmatic arc, back-arc basin. In the Alps, the Bio unit might be also an oceanic basin that separated the Sesia block from Apulia. Ch: Chenaillet, HF: Helminthoid flysch. PF: future Penninic front. To the North, the Valais ocean separated the Briançonnais block from Europe. In the Variscan belt, the Carboniferous tectonic, metamorphic, and magmatic features developed in the Moldanubian Domain are located in the upper plate [from Lemoine et al., 2000, Faure et al., 2005, 2008].

5. The collisional stage

5.1. *Western Alps: suturing of the Liguro-Piemonte ocean*

The contact between two continents, i.e. collision, was preceded by continental subduction as demonstrated by the HP and UHP metamorphism recognized in the Internal Crystalline Massifs (Dora Maira, Gran Paradiso) and Briançonnais zone [Chopin, 1984, Agard et al., 2002, Beltrando et al., 2010, Lardeaux, 2014b; Figure 7]. The nappe stacking from the SE to the NW that developed during this stage is documented by the shift of radiometric ages from Paleocene (ca. 50 Ma) to Miocene (ca. 10 Ma) [Monié and Philippot, 1989, Ford et al., 2006, Bonnet et al., 2022]. The sedimentary record also shows a NW-ward migration of the terrigenous deposits. The erosion of the early reliefs in the Internal zone supplied the material for the Middle Eocene (ca. 40 Ma) Briançonnais black flysch, then in the Outer zone, the Priabonian (35 Ma) grès d'Annot-Aiguilles d'Arves flysch, and the Rupelian (ca. 30 Ma) Dauphinois flysch.

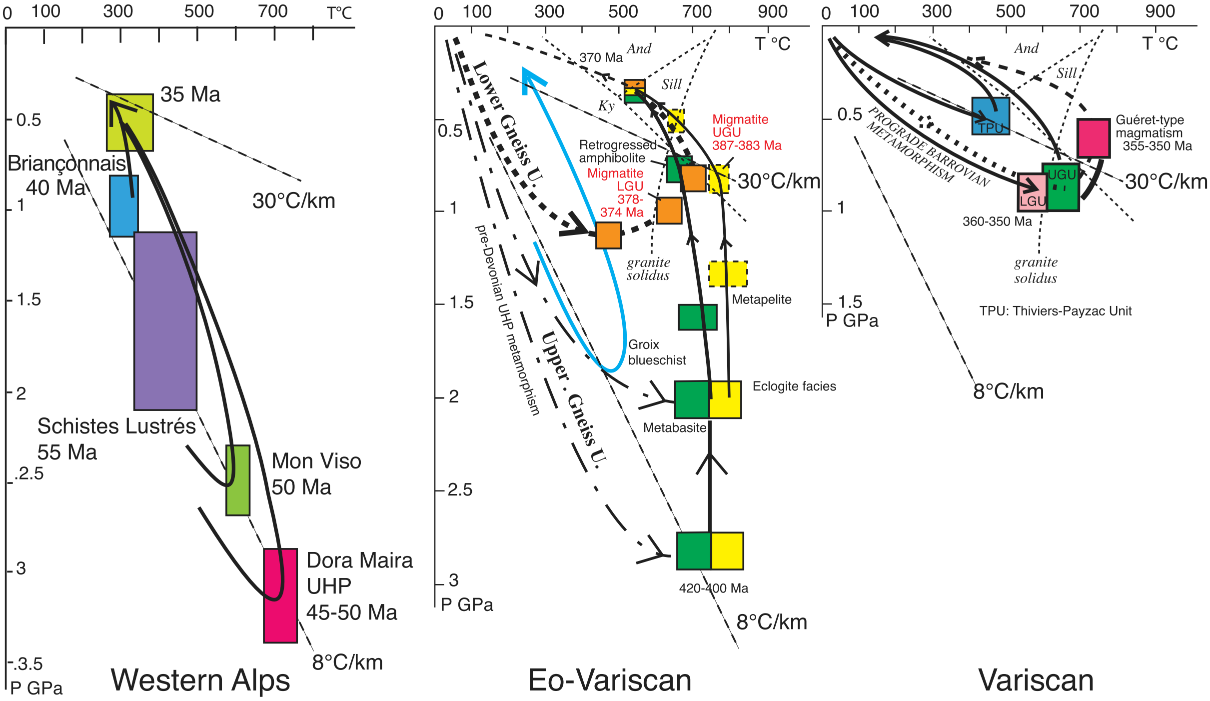

Figure 7. Compared PT paths for the Western Alps, Eo-variscan and Variscan Moldanubian domains [modified from Agard and Lemoine, 2005, Bosse et al., 2005, Faure et al., 2009, Lardeaux, 2014a,b]. Note the contrast between cold (8 °C/km) and hot (30 °C/km) thermal gradients in the Alpine and Variscan belts, respectively.

The syn-tectonic molassic sedimentation in the foreland basin continued until the Miocene (10 Ma).

Although the structural style and thermobarometric conditions may change along the strike of the belt, the general architecture of the Western Alps is acknowledged from top to bottom with: (i) an uppermost Austroalpine continental crust domain overlying (ii) the Liguro-Piemonte oceanic sedimentary and magmatic rocks, in turn overlying (iii) the Briançonnais sedimentary nappe stack that overthrusts along the Penninic thrust iv) the less deformed and metamorphosed Dauphino-Helvetic domain (Figure 3). Microtectonics document a general top-to-the-NW ductile shearing. However, during the Miocene, a SW-ward nappe displacement developed in the S. part of the Dauphinois zone (Figure 3).

5.2. *The Eo-Variscan Gondwana–Armorica: suturing of the Medio-European ocean*

HP to UHP eclogites and granulites are exposed in the Moldanubian domain [S. Brittany, Vendée, Limousin, Marvejols, Lyonnais areas; e.g. Faure et al., 2005, Lardeaux, 2014b; Figure 7]. As mentioned above, the protoliths of these rocks are not ophiolites but mafic and felsic dykes and sills emplaced during the early Ordovician rifting within a thinned continental crust. The UHP assemblages argue for ca 100 km deep continental subduction [Lardeaux et al., 2001, Berger et al., 2010]. The age of the Eo-variscan HP metamorphism is still disputed: either around 415–400 Ma [Pin and Lancelot, 1982, Do Couto et al., 2016] or 370–360 Ma [Bosse et al., 2000, Paquette et al., 2017, Lotout et al., 2018]. At the lithosphere scale, the collision between Gondwana and Armorica was responsible for a nappe stack, from top-to-bottom: (i) the Mauges nappe derived from Armorica, (ii) the ophiolitic units derived from the Medio-European Ocean, (iii) the (U)HP metamorphic units, referred to as the Upper Gneiss Unit, (iv) the Lower Gneiss unit. The last two units derived from stretched, or hyperextended, Gondwana continental crust. It is worth to note that the lowermost units, Para-autochthonous and Fold-and-Thrust belt, did not experienced the Eo-variscan tectono-metamorphic events.

Moreover, an important difference between the Alpine and Eo-variscan orogens is the development in the latter of a pervasive crustal melting coeval with the exhumation of the HP rocks (Figure 7). Migmatites are widespread in the paragneiss of the Upper and Lower Gneiss units. After the continental subduction, the UGU underwent an adiabatic decompression that retrogressed the eclogites into garnet amphibolites. In the same time, the Al-rich metapelites and felsic orthogneiss were melted to produce the metatexites observed in the Champtoceaux, Limousin, Sioule, Haut Allier, Lyonnais, and Rouergue areas. The migmatites in the UGU and LGU yield zircon U/Pb ages at 385–380 Ma and 380–375 Ma, respectively [Faure et al., 2008]. They exhibit a NE–SW striking mineral lineation coeval with top-to-the-SW shearing that suggest syn-convergence exhumation. In Morvan, Devonian migmatites that include eclogites and retrogressed garnet amphibolites [Godard, 1990] are older than Frasnian (ca. 383–372 Ma) sedimentary rock [for details see Leloix et al., 1999, Faure et al., 2005].

5.3. *The Variscan collisions: suturing of the Rheic and Tepla-Le Conquet ocean*

The Variscan orogeny *stricto sensu* corresponds to the closure of the Rheic and Tepla-Le Conquet oceans through S-directed subductions (Figure 6). The collision of Laurussia with Saxo-Thuringia gave rise to N-displaced Lizard ophiolitic klippe in SW England. The collision of Saxo-Thuringia with Armorica was responsible for the N-directed syn-metamorphic nappes exposed in the Léon block. In other places, similar structures are concealed beneath the sedimentary rocks of the Paris basin, as shown by the ECORS seismic profile [Cazes et al., 1985]. The Variscan collisions reworked the Eo-Variscan structures of the Moldanubian domain in the Massif Central and S. Armorican massif. It is worth to note that this domain belongs to the upper plate. A top-to-the NW ductile shearing, coeval with a MP/MT metamorphism, developed in the Famennian–Tournaisian [ca. 360–350 Ma; Figure 6; Faure et al., 2009, Do Couto et al., 2016]. This event, called “Bretonian phase” was recognized in Central Brittany by the erosional gap of Late and Middle Devonian formations, and Tournaisian unconformity [Cogné, 1965, Paris et al., 1982, Rolet, 1982, Faure et al., 2017]. In NE Massif central, the northwestward shearing was responsible for emplacement of the Brévenne back-arc ophiolitic rocks on top of the retrogressed Eo-Variscan gneiss [Leloix et al., 1999, Faure et al., 2005].

The final S-directed nappe stacking, coeval with greenschist facies conditions, occurred in Visean-Bashkirian (ca. 340–320 Ma) in the hinterland basin of Southern Massif Central, Pyrenees and Vendée. In Montagne Noire and Pyrenees, thrusting was a syn-sedimentary event with a turbiditic sedimentation [Engel et al., 1978, Delvolvé et al., 1998]. A similar pattern is recognized in the northern foreland basin: Ardenne, SW England [Figure 4; e.g. Fielitz and Mansy, 1999].

6. The intracontinental syn- to late convergence

6.1. *Western Alps*

In the Inner zone, the exhumation of the metamorphosed oceanic and continental units was accommodated by ductile normal faults, such as the Monviso one [Ballèvre et al., 1990]. Although not exposed in the Western Alps, a HT/LP (metamorphism developed during the Oligocene (28–21 Ma) in the Lepontine dome [Figure 2, Berger et al., 2020]. The sillimanite and K-feldspar isogrades, oblique to the thrust contacts, define an elliptical domal shape. The Bergell granodiorite emplaced along the Tonale line. The Miocene exhumation of the External Crystalline Massifs accommodated by thrusting [e.g. Leloup et al., 2005, Egli et al., 2017] was coeval with belt parallel extension [Sue et al., 2007]. In the External zone, intracontinental shortening was responsible for the NW- and SW-ward thrusting of the Dauphino-Helvetic Mesozoic series upon the molassic deposits (Figure 2). Sismotectonics, stress tensor analyses and geodetic data reveal a complex tectonic pattern with a small displacement rate (ca. 1–2 mm/yr) accommodated by thrusting in Jura and Po plain, and belt-transverse extension in the Internal zone. GPS data and paleomagnetism argue for a counterclockwise rotation of Apulia. Thus, the origin of the present tectonics results from both body forces due to gravitational re-equilibration of the thickened crust, and far-field boundary forces related to Apulia indentation.

6.2. *Variscan belt*

Intracontinental tectonics likely related to the exhumation of the Eo-Variscan rocks are not documented. On the contrary, the Variscan late to post-orogenic stage is recorded by magmatic, tectonic, and sedimentary processes. The Variscan orogen displays a large amount of magmatic rocks emplaced from Late Tournaisian (biotite–cordierite Guéret massif) to Gzhelian. Carboniferous migmatites are widespread from the Léon block to the Pyrenees, through South Armorica, Vendée, Massif Central, and Central Vosges. The migmatites, formed at the expense of metasediments and orthogneiss, are dated between 330 and 325 Ma, with younger ages around 315–305 Ma close to post-migmatitic intrusions [Bé Mézème et al., 2006, Turrillot et al., 2011, Augier et al., 2015, Trap et al., 2017, Vanderhaeghe et al., 2020]. The tectonic setting of the domes, namely, diapiric, compressional, extensional, or transcurrent, will not be discussed here [for details see Van Den Driessche and Brun, 1992, Echtler and Malavieille, 1990, Faure, 1995, Franke et al., 2011, Denèle et al., 2014].

The Late Visean magmatism is also represented by the “Tufs anthracifères” volcanic-sedimentary series exposed in the NE part of the Massif Central and S. Vosges. The emplacement of this series that consists of undeformed and unmetamorphosed felsic and intermediate-type lava flows, pyroclastites, sandstone, siltstones, and coal measures, was controlled by a NW–SE stretching during the onset of the late orogenic extension in the northern Moldanubian Domain, whereas the thickening event was still active in the S. Massif central, and Pyrenees. In the Northern Massif central, the “red granites” and microgranites of the Montagne Bourbonnaise represent the deep part of this late orogenic magmatic suite.

Due to different crustal sources, per-aluminous two-mica granites and porphyritic monzogranites of Serpukhovian to Bashkirian age (ca. 325–310 Ma) are distinguished [Didier and Lameyre, 1969]. The former group is well represented in S. Brittany, Vendée, and Limousin, and the latter is mainly exposed in NE and SE Massif central. Both pluton types are syntectonic bodies characterized by a NW–SE stretching recorded in the plutons, contact aureole, and country rocks. Ductile normal faults coeval with pluton emplacement support an extensional setting. In the Armorican Massif, the syn- to late-orogenic plutonism was associated with dextral strike-slip faults of the S. Armorican and N. Armorican shear zones [Jégouzo, 1980].

During the late Carboniferous, the Massif Central and Armorican massif experienced a second extensional event ascribed to the post-orogenic stage. The opening of coal-bearing intramontane basins was controlled by normal or strike-slip faults with a NNE–SSW maximum stretching direction [Malavieille et al., 1990, Faure, 1995]. The Velay granite-migmatite dome formed also during this late Carboniferous event [e.g. Barbey et al., 2015, Moyen et al., 2017, Laurent et al., 2017]. Mg–K magma, widespread in the NE Massif Central and Vosges, formed by the melting of a mafic lower crust with some mantle input. Lamprophyre dykes are also interpreted as a consequence of asthenospheric upwelling. The HT granulite xenoliths in the Neogene lava record a HT/LP metamorphism similar to the one observed in the Alpine Ivrea zone or some Pyrenean massifs (Castillon, Agly). These rocks form the layered lower crust depicted in the ECORS seismic profile [Cazes et al., 1985].

7. Conclusive remarks

This brief review of the main features of the Variscan and Alpine orogens shows that these belts resulted of crustal thickening due to nappe stacking after the closure of oceanic domains. The main features related to the geodynamic evolution stages of the W. Alps, Eo-variscan, and Variscan belts are listed in Table 2. Moreover, the Eo-variscan, Variscan, and Alpine belts exhibit some differences that can be related to the diversity of the thermal gradients and crustal inheritance.

7.1. *Passive continental margins*

As introduced in Section 3.2, the pre-Variscan Ordovician passive continental margin resemble the magma-rich margins [e.g. Geoffroy, 2005]. This feature represents a significant difference with the Jurassic Alpine continental margin in which syn-rift magmatism is absent [e.g. Lemoine et al., 2000]. One explanation might be that the Ordovician rifting was accommodated by a higher strain rate than in the Alps, allowing a fast mantle denudation that enhanced crustal melting.

Table 2. Compared geodynamic evolution stages of the W. Alps, Eo-variscan, and Variscan belts

	Western Alps	Devonian Eo-Variscan belt	Carboniferous Variscan belt
PRE-OROGENIC *Continental rifting to ocean opening*	Triassic rifting in Apulia and Briançonnais. Normal faulting in External Crystalline Massifs, no magmatism	Late Cambrian Early Ordovician rifting Leptynite-amphibolite complex Sardic/Ardennian unconformity Drain ophiolites	Late Cambrian Early Ordovician rifting and Le Conquet ophiolites
	Liguro-Piemonte ocean (Middle Jurassic)	**Medio European ocean** (Early Ordovician)	**Rheic & Tepla oceans** (Early Ordovician)
OROGENIC	Helminthoid flysch: trench fill Schistes Lustrés	Ile de Groix (subduction melange ?)	Not exposed in France
Oceanic subduction	(U)HP metamorphism (Monviso)		
Magmatic arc	Absent	Ligerian arc (inferred)	Morvan arc Limousin tonalites
Back-arc basin	Absent	St-Georges/Loire back-arc basin	Brévenne Back-arc ophiolite
Continental subduction	Austroalpine nappe Internal Crystalline Massifs Penninic recumbent folds	Mauges nappe Moldanubian syn-metamorphic thrusting	Saxo-Thuringian (Léon): top-to-the N shearing Moldanubian: Top-to-the NW thrusting
Collision	Schistes Lustrés nappe	HP-UHP metamorphism (eclogites, HT granulites)	Reworking of Eo-Variscan structures MP/MT metamorphism
Intracontinental thrusting		MP/MT metamorphism Upper Gneiss Unit thrusting upon Lower Gneiss Unit	
	E → *W* migration of flysch basins Helvetic recumbent folds Dauphinois Fold-and-Thrust belt Briançonnais nappes		Moldanubian: Para-autochthonous Unit South-directed Fold-and-Thrust belt (Montagne Noire, Pyrenees) Rheno-Hercynian: North-directed Fold-and-Thrust belt (Ardenne, SW England)
LATE TO POST-OROGENIC	Central Alps: Lepontine dome Biella, Bergell, Adamello plutons		Visean marine deposits Tufs Anthracifères Two-mica granites Monzogranite Mg–K granites
Crustal melting	Migmatites	Devonian migmatites	Carboniferous Migmatite
Foreland basin	Helvetic molasse Po plain molasse	Not documented	North foreland basin South hinterland basin
Intramontane basin	Not documented	Not documented	Gzhelian coal basins

7.2. *Crustal melting*

In the Western Alps, evidence for crustal melting is absent. Migmatites are restricted to the Lepontine dome in Central Alps. The rare Oligocene plutons represent a few volume compared to the huge mass of the Variscan ones. It might be argued that Alpine granites are not yet exposed to the surface. However, as UHP rocks are already exhumed from ca. 90 km, a large amount of plutons would be expected as well. A possible cause for the rarity of Alpine melting could be that the middle and lower crusts are formed by unfertile rocks left after the Variscan melting. The Paleozoic rocks that already released melts were unable to produce new magmas in the Cenozoic. The difference in crustal melting behavior reflects the contrasted thermal gradients recognized in cold and hot orogens. The Alpine one of ca. 8 °C/km was colder than the Eo-variscan and Variscan gradients of ca 20–30 °C/km (Figure 7). However, the Eo-variscan prograde metamorphic gradient is also estimated at 8 °C/km before reaching a 30 °C/km one during exhumation. It has also been shown that in the northern part of the Massif Central, the Late Visean thermal imprint was able to reset the ^{40}Ar/^{39}Ar chronometer [Faure et al., 2002]. These observations raise the question of the origin of heat. On the basis of the Himalayan case, it is often argued that the increase in radiogenic elements due to crustal thickening triggered the melting of hydrated rocks to produce per-aluminous magmas [Lameyre, 1984]. Although this mechanism likely played a role, the widespread distribution of migmatites and granites throughout the entire belt, even in the weakly thickened external zone, is hardly explained by an intracrustal heat source. Alternatively, a mantle source can be envisioned. Mantle convection, lithosphere mantle delamination or slab breakoff would allow the rise of hot asthenosphere bringing enough heat to melt the continental crust.

7.3. *Fluid circulation and ore deposits*

The Variscan belt is famous for its metallic resources mined since Celtic times. Au, Sb, W–Sn, Li–Be ore deposits are displayed in the French Variscan massifs [e.g. Chauris and Marcoux, 1994, Bouchot et al., 1997, Marignac and Cuney, 1999]. These deposits are linked to the late- or post-orogenic hydrothermal and magmatic episodes. Massive sulfide deposits are exposed in the S. Iberian pyrite belt, or in the NE Massif Central where they are associated either to the Morvan magmatic arc or Brévenne back-arc basin developed during the oceanic subduction stage. In contrast, ore deposits are rare in the Western Alps. As exceptions, the St-Véran, Servette-Chuc and Praborna mines, and scattered small sized Cu deposits are recognized in the ophiolites of the Schistes Lustrés nappe, but they are related to the pre-orogenic hydrothermal events. Thus a dry and sterile Alpine crust is at variance with an hydrated, fertile Variscan one. Furthermore, the "cold" temperature gradient was unable to enhance fluid circulations.

7.4. *The basement question*

In the Alps, nappe stacking involves Meso-Cenozoic sedimentary rocks and Paleozoic metamorphic or magmatic rocks shaped up during the Variscan orogeny [e.g. Faure and Ferrière, 2022, and references therein]. In the Variscan belt, a Neoproterozoic Cadomian basement exists in Armorica and Saxo-Thuringia, even not exposed in the Léon block. In the Moldanubian domain, Neoproterozoic sedimentary and magmatic rocks do exist, but they cannot be considered as a basement since they experienced their first deformation only during the Variscan orogeny. There, reference to "Cadomian" events is therefore groundless in this domain. The lithological contrast between "soft" and "hard" rheologies might be also the cause for the different structural styles between the Moldanubian and Armorican domains.

7.5. *Orogenic time scale*

The ignorance of several parameters such as the precise age and thermal state of the oceanic lithosphere, or the dip angle of the subducting slab, does not allow us to accurately depict the geodynamics of the converging lithospheres. Nevertheless, a rough computation provides a semi-quantitative estimate of the different stages of the Eo-variscan, Variscan and Alpine orogenic evolution. From a Callovian–Oxfordian age (~160 Ma) for the opening of the Liguro-Piemonte ocean and an early Eocene age (~55 Ma) for the continental subduction or incipient collision, the life-time of the Liguro-Piemonte ocean was about 105 My. In contrast, the Medio-European ocean was a short lived one, ca. 80 My, from the Early Ordovician (~480 Ma) break-up of Pannotia to the Eo-variscan collision at ca. 400 Ma. The Rheic Ocean also opened in Early Ordovician, but closed in Early Carboniferous (~360 Ma). This 120 My long duration might account for the development of arc and back-arc basins.

In the Alps, the collisional stage lasted ~45 My from Ypresian (55 Ma) to Tortonian (10 Ma). The duration of the Eo-variscan collision to post-collision stages is difficult to estimate since Devonian molasse is not documented. A minimum 30 My time lapse is assumed from continental subduction (~400 Ma) to migmatisation (~370 Ma). From the Tournaisian (360 Ma) to late Carboniferous (Gzhelian 300 Ma), the

Variscan collision duration (60 My) was longer than the Alpine and Eo-variscan orogenic ones.

The Eo-variscan and Variscan orogenies document multiple collisions in space and a polycyclic orogenic history in time. With a single cycle, the case of Western Alps is simpler, but a more complex evolution might be accepted for the entire Alpine belt if the Valaisan ocean of Central Alps is considered. Furthermore, it can be argued that the Alpine cycle is not completed yet since the African plate is still subducting below Europe (Figure 1). After the closure of the Tyrrhenian and Aegean back-arc basins, the Alpine orogen might also present a bivergent architecture, and a polyorogenic evolution similar to the Variscan one.

Conflicts of interest

The author has no conflict of interest to declare.

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